Instrumentation

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Jürgen Engelfried[1]
Instituto de Física, Universidad Autónoma de San Luis Potosí, Mexico

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Outline

three 75min classes, roughly separated in:

- Physics of Particle Detection
- Basic Designs of Detectors, with real examples from real experiments
- Special Example: Particle Identification

Please ask questions, be active, do not just consume!

[1] jurgen@ifisica.uaslp.mx, http://www.ifisica.uaslp.mx/~ jurgen

Introduction

- Detection and Identification of Particles and Nuclei important in
  - high-energy physics
  - cosmic ray physics
  - nuclear physics

Basic Idea
Every effect of particles or radiation can be used as a working principle for a detector

Main Purpose of particle detectors:
Detection and identification of particles with mass m and charge z
In particle physics: Usually $z = 0, \pm 1$, but not in nuclear, heavy ion physics, or cosmic rays

Examples

- Charged particle (charge z) deflected in magnetic field $\rightarrow$ momentum p

$$\rho \propto \frac{p}{z} = \frac{\gamma m \beta c}{z}$$

- Time of flight determines particle velocity

$$\beta = \frac{v}{c} \propto \frac{1}{t}$$

- Cherenkov angle determines particle velocity

$$\theta_C = \frac{1}{\beta n}$$

- Calorimeter measurement provides energy measurement

- Charge measurement: Ionization Energy loss

$$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$$

- With all the information together one can determine the quadri-vector of the particle.

- Basic detection techniques work mostly for charged particles only.

- Neutral particles usually detected "indirectly" via production of charged particles.

Introduction (cont.)

Design of Instrumentation and Detectors requires knowledge of

- Basic physics for interaction of charged and neutral particles with matter
- Mechanical Engineering
- Electrical Engineering (high voltage)
- Electronic Engineering
- Interfaces to Trigger, Data Acquisition and Computing (Lecture by Nick Elis)
- Software Engineering (calibration)
- Operation (stability)

- To know any one of them is not sufficient
- You have to apply **all together** to build, operate and **use** an instrument for your **physics measurement**

- **Always keep in mind what you want to measure, and what precision (resolution) you need**

Recommended Literature

- Claus Grupen: Particle Detectors. Cambridge University Press, 2000.
  The best book I know about detectors.
- Konrad Kleinknecht: Detectors for particle radiation. Cambridge University Press, 2nd edition 1998.
  Also a good book.
- Richard C. Fernow: Introduction to experimental Particle Physics. Cambridge University Press, 1986.
- Richard Wigmans: Calorimetry. Oxford Science Publishing, 2000.
  THE book about calorimeters. Written by the expert with all details.
- Lecture notes and Proceedings of ICFA Instrumentation Schools (since 1987 every two years).
- Particle Data Book. short summaries of important things.

Outline of first part of lecture

- Introduction, Kinematics
- Interaction of Charged Particles
  - Ionization, scintillation, Cherenkov and Transition Radiation
  - Bremsstrahlung and nuclear interactions
- Interaction of Neutral Particles
  - photons: photoelectric effect, Compton scattering, pair production
  - neutrons
  - neutrinos
- Electromagnetic Showers
- Hadron Showers

Charged Particles – Kinematics

- Conservation of Momentum and Energy: Max. Energy for particle with mass m, velocity $v = \beta c$, collision with electron:

$$E_{\text{kin}}^{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma \frac{m_e}{m} + \left(\frac{m_e}{m}\right)^2} = \frac{2m_e p^2}{m^2 + m_e^2 + 2m_e E/c^2}$$

- Limits:
  - Low energy, heavier than electron $(2\gamma \frac{m_e}{m} \ll 1,\, m \gg m_e)$

$$E_{\text{kin}}^{\max} = 2m_e c^2 \beta^2 \gamma^2$$

  - relativistic ($E_{\text{kin}} \approx E$, $pc \approx E$):

$$E^{\max} = \frac{E^2}{E + m^2c^2/2m_e}$$

  - Electron – Electron Collisions ($m = m_e$):

$$E_{\text{kin}}^{\max} = \frac{p^2}{m_e + E/c^2} = \frac{E^2 - m_e^2 c^4}{E + m_e c^2} = E - m_e c^2$$

- Scattering angle (on nucleus Z, impact parameter b)

$$\Theta = \frac{2z \cdot Z \cdot e^2}{\beta c b} \cdot \frac{1}{p}$$

- Cross Section (Rutherford):

$$\frac{d\sigma}{d\Omega} = \frac{z^2 Z^2 r_e^2}{4} \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \Theta/2}$$

- Multiple Scattering

$$\sqrt{\langle \Theta^2 \rangle} = \Theta_{\text{plane}} = \frac{13.6\,\text{MeV}}{\beta c p} z \cdot \sqrt{\frac{x}{X_0}} \left\{1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right\}$$

$$\Theta_{\text{space}} = \sqrt{2}\, \Theta_{\text{plane}}$$

Approximation by Gaussian:

$$P(\Theta) d\Theta = \frac{1}{\sqrt{2\pi}\Theta_{\text{plane}}} \exp\left\{-\frac{\Theta^2}{2\Theta_{\text{plane}}^2}\right\} d\Theta$$

Energy Loss of Charged Particles

- Interaction via exchange of Photons (electromagnetic interaction)
- Virtual Photons: Absorbed by atoms in material $\longrightarrow$ Ionization, Excitation
- Real Photons: Radiation is emitted by a charge particle if:

  1. $v > c/n$: Cherenkov radiation
  2. $\vec{v}/c_{\mathrm{ph}} = \vec{v} \cdot n/c$ changes
     (a) $|\vec{v}|$ changes: Bremsstrahlung
     (b) direction of $\vec{v}$ changes: Synchrotron radiation
     (c) n changes: Transition Radiation

Ionization Energy Loss (Bethe-Bloch formula)

Derivation from Claus Grupen

$$p_b = \frac{2 r_e m_e c}{b \beta} z$$ Momentum transfer per target electron b: impact parameter

Energy transfer (classical approximation)

$$\epsilon = \frac{p_b^2}{2m_e} = \frac{2 r_e^2 m_e c^2}{b^2 \beta^2} z^2$$

Interaction rate per (g/cm^2), atomic cross section σ

$$\Phi[\mathrm{g}^{-1}\mathrm{cm}^2] = \frac{N_A}{A}\sigma[\mathrm{cm}^2/\mathrm{atom}]$$ N_A Avogadro's number, A atomic mass

$$\Phi(\epsilon)\, d\epsilon = \frac{N_A}{A} 2\pi b\, db\, Z$$

$2\pi b\, db$ area of annulus Z Number of electrons per atom

Bethe-Bloch (cont.)

$$\epsilon = \epsilon(b) \Rightarrow b^2 = \frac{2r_e^2 m_e c^2}{\beta^2}\, z^2\, \frac{1}{\epsilon}$$

$$\Phi(\epsilon)\, d\epsilon = \frac{N_A}{A}\, \pi\, \frac{2r_e^2 m_e c^2}{\beta^2}\, z^2\, Z\, \frac{d\epsilon}{\epsilon^2}$$

energy loss

$$-dE = \int_0^\infty \Phi(\epsilon)\, \epsilon\, dx = \int_0^\infty \frac{N_A}{A}\, 2\pi\, b db\, Z\, \epsilon\, dx$$

$$-\frac{dE}{dx} = \frac{2\pi N_A}{A}\, Z \int_0^\infty \epsilon\, b\, db = 2\pi\, \frac{Z\, N_A}{A}\, \frac{2r_e^2 m_e c^2}{\beta^2}\, z^2 \int_0^\infty \frac{db}{b}$$

Problem: Integral is divergent at $b \longrightarrow 0$ and $b \longrightarrow \infty$

Bethe-Bloch (cont.)

$b \to 0?$ assume $b_{\text{min}} = \frac{h}{2p} = \frac{h}{2\gamma m_e \beta c}$

half the de Broglie wavelength

$b \to \infty?$ if revolution time τ_R of electron in target atom is smaller than interaction time τ_i target looks neutral

$\tau_i = \frac{b_{\text{max}}}{v}\sqrt{1-\beta^2}$ Lorentz contraction

$\tau_R = \frac{1}{v_Z \cdot Z} = \frac{h}{I}$

mean excitation energy $I \approx 10\,\text{eV} \cdot Z$

$\tau_i = \tau_R \qquad \Rightarrow b_{\text{max}} = \frac{\gamma h \beta c}{I}$

$$-\frac{dE}{dx} = 2\pi\ \frac{Z\,N_A}{A}\frac{2r_e^2 m_e c^2}{\beta^2} z^2 [\ln \frac{2\gamma^2\beta^2 m_e c^2}{I} - \eta]$$ η: screening effect

Bethe-Bloch (cont.)

Exact treatment: Bethe-Bloch formula (summary in PDG)

$$-\frac{dE}{dx} = 2\pi \frac{Z\,N_A}{A} \frac{2\,r_e^2\,m_e\,c^2}{\beta^2} z^2 [\frac{1}{2} \ln \frac{2\,m_e\,c^2 \gamma^2 \beta^2}{I^2} \beta^2 - \frac{\delta}{2}]$$

density correction

$$\frac{\delta}{2} = \ln \frac{\hbar\omega_p}{I} + \ln \beta\gamma - \frac{1}{2}$$

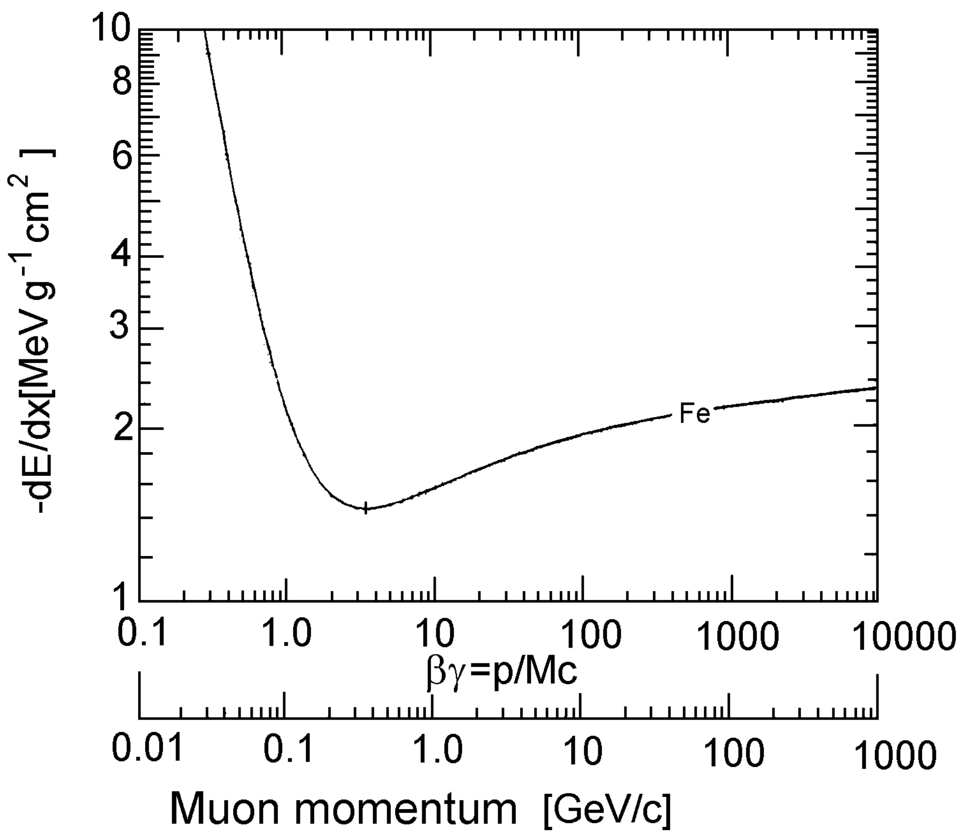
$$\hbar\omega_p = \sqrt{4\pi N_e r_e^2}\,\frac{m_e\,c^2}{\alpha}$$ plasma energy

N_e electron density of absorbing material

α fine structure constant

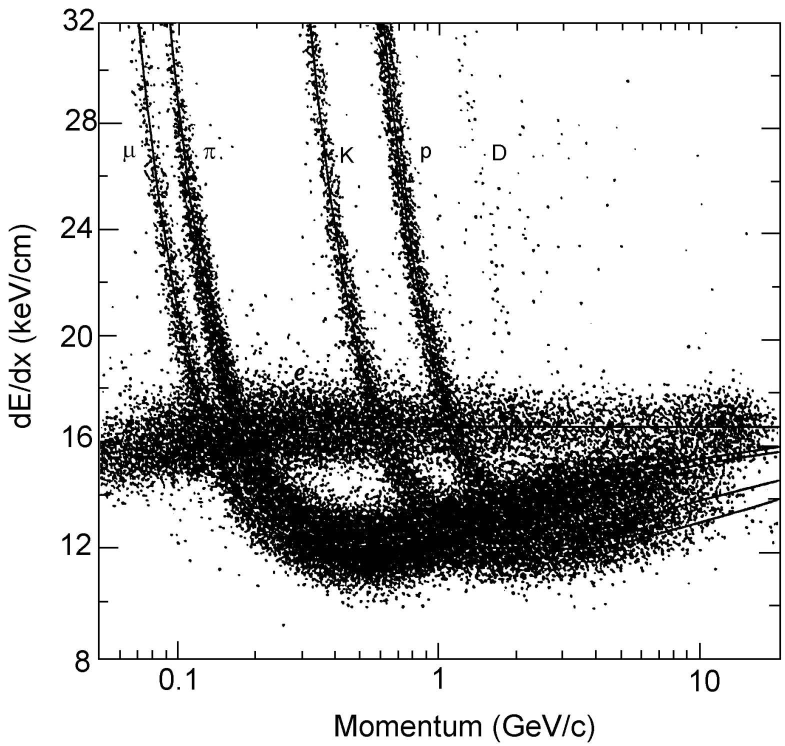
Bethe-Bloch (cont.)

Example:
Energy loss of muons in iron



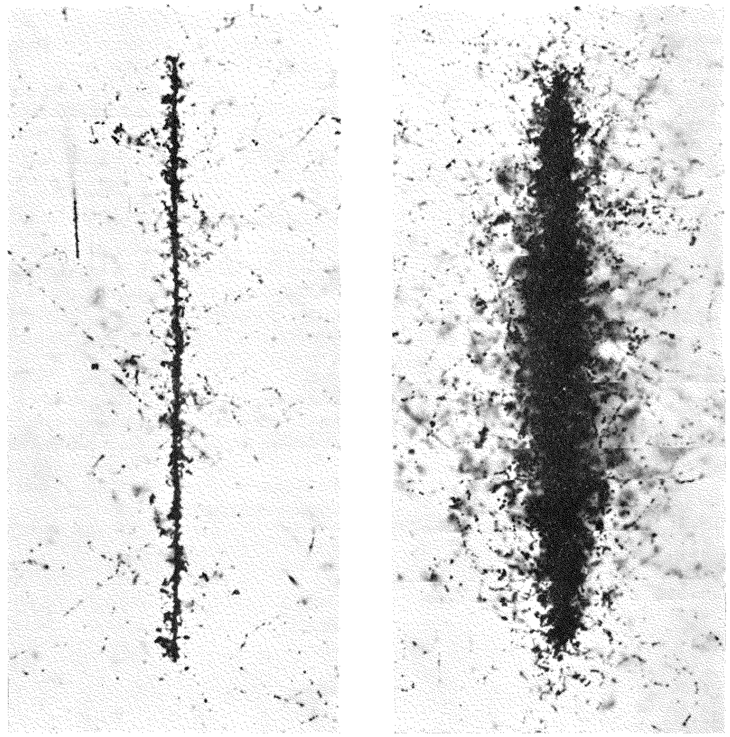
- Minimum at $3 \leq \beta\gamma \leq 4$
- Minimum ionizing particles:
  - helium: $-dE/dx = 1.94\,\mathrm{MeV/(g/cm^2)}$
  - uranium: $-dE/dx = 1.08\,\mathrm{MeV/(g/cm^2)}$
  - hydrogen: exceptionally large $(Z/A = 1)$
- $\ln\gamma$ term: relativistic (logarithmic) rise
- Fermi-Plateau due to density effect
- in gases: Plateau $\approx 60\,\%$ higher as min. ion.

Energy Loss in Gases



PEP4/9-TPC (185 dE/dx measurements, Ar:CH_4 at 8.5 atm)

Energy Loss for Heavy Ions



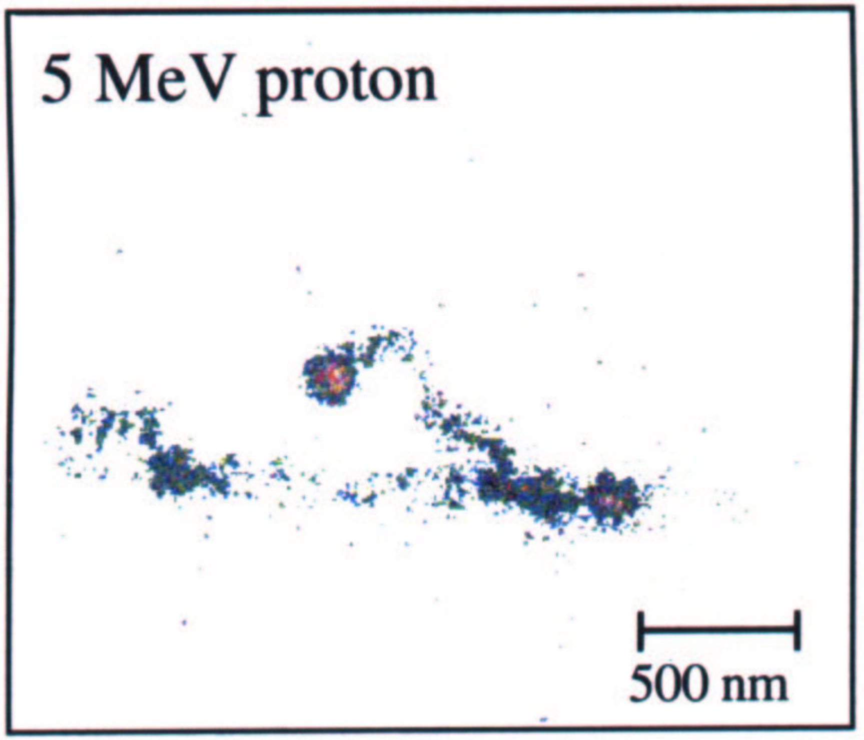
Fe $Z = 26$ $\qquad$ $Z = \sim 90$

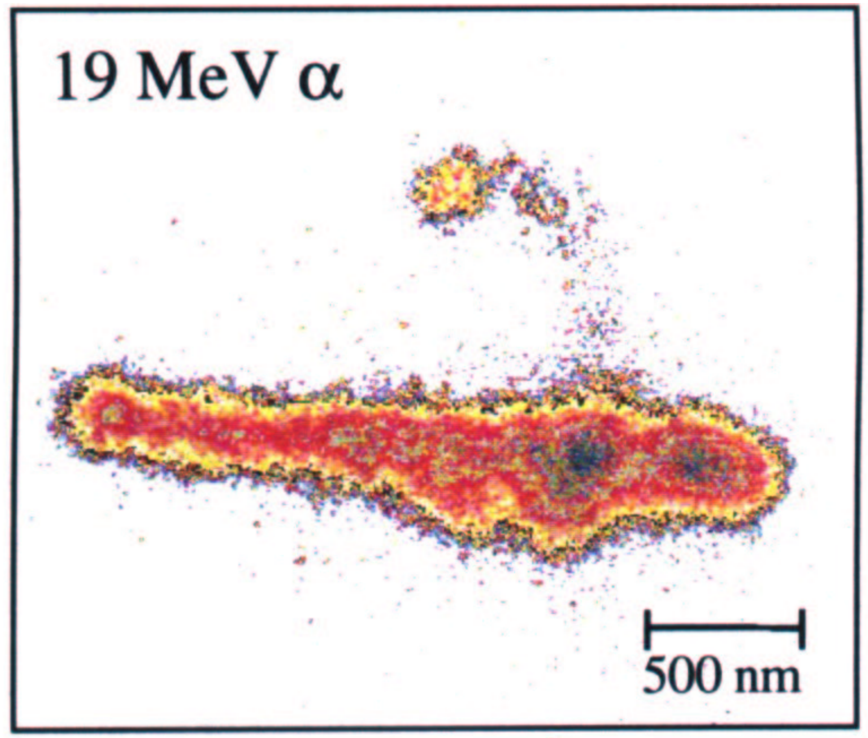
$$z = 26 \qquad\qquad z \approx 90$$

Cosmic Radiation in Nuclear Emulsions $\qquad (dE/dx \propto z^2)$

G.D. Rochester, Advancement in Science, Dec. 1970, pp. 183-194

Energy Loss in Optical Micro-dosimeter





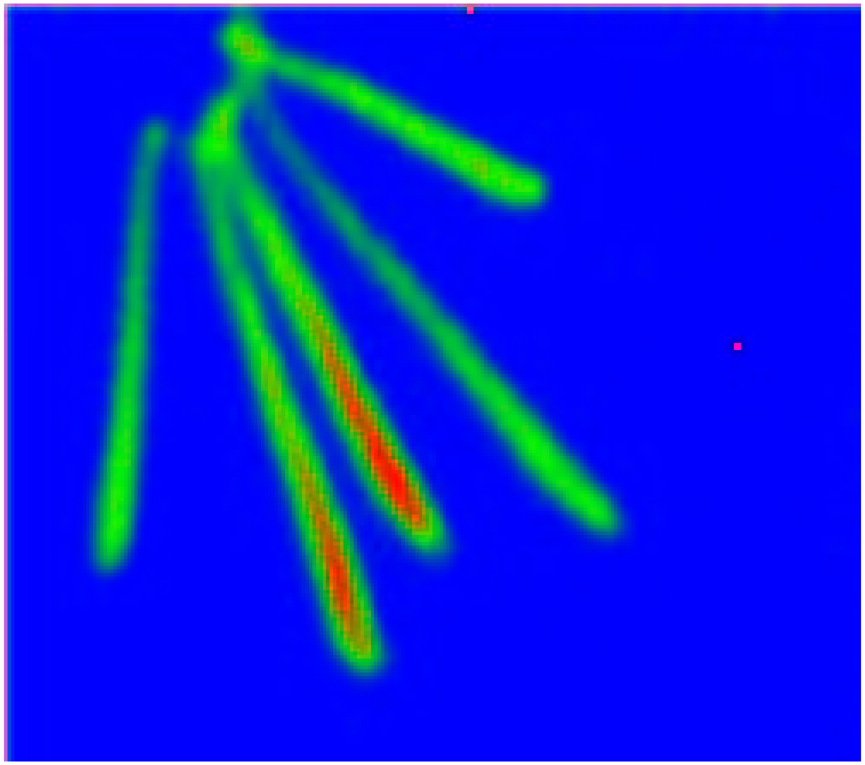
$$\frac{dE}{dx}|_\alpha \gg \frac{dE}{dx}|_p$$

$$\frac{dE}{dx} \propto z^2$$

note increase of ionization at end of track, also the δ-rays

U. Titt et al., Nucl. Instr. Meth. A416 (1998) 85

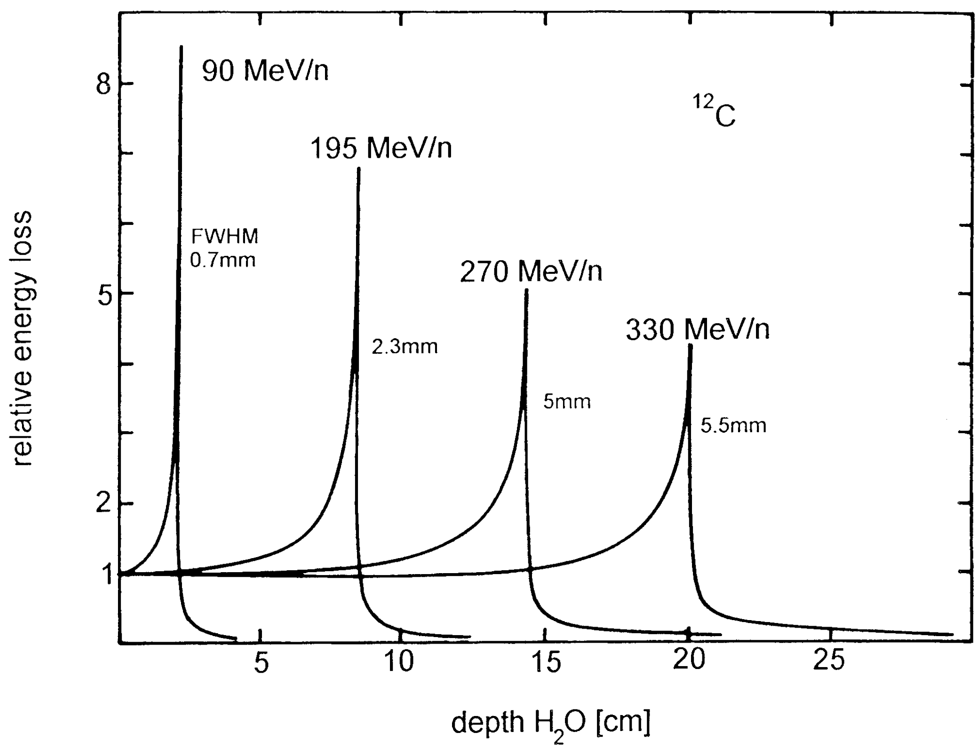
Energy Loss in Gas

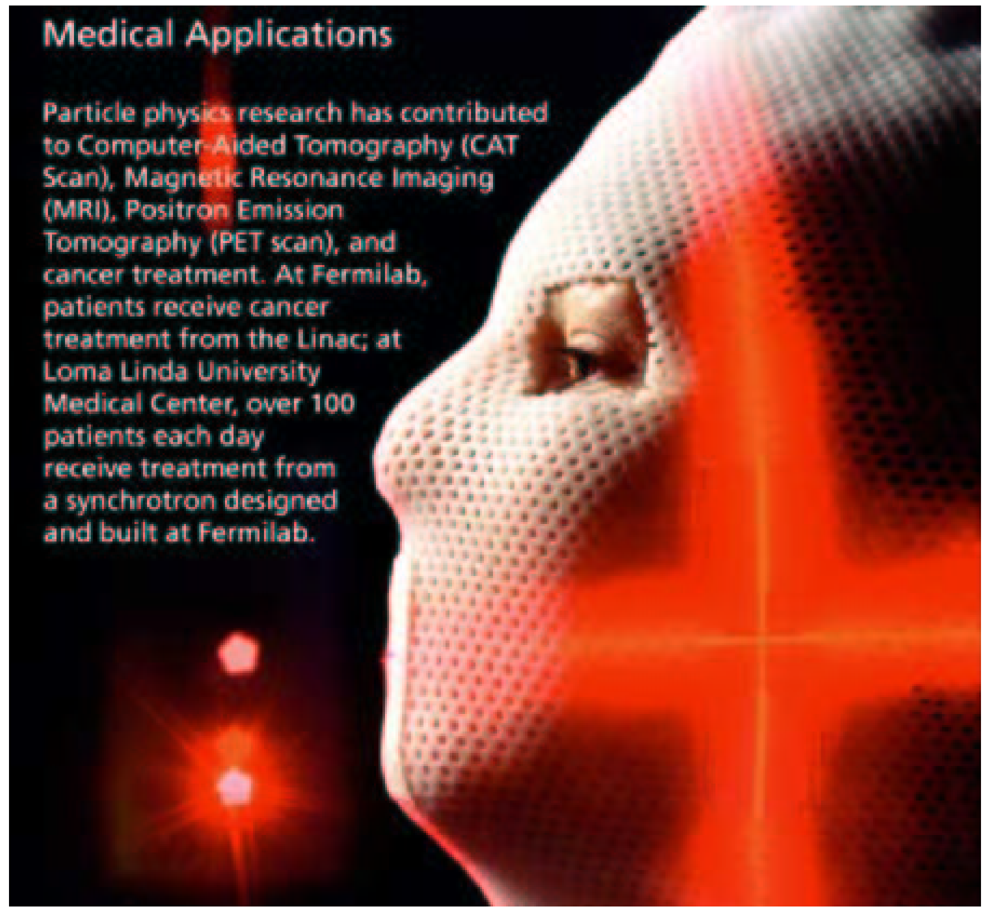


α particles in CF_4 based gas mixture, recorded via scintillation in double-gem micro-strip gas chamber

F.A. Fraga et al., Proceedings of Nucl. Sci. Symp. and Medical Imaging Conference, Seattle, Oct. 199

Application: Bragg Peak





^{12}C ions in water. Treatment of deep-seated tumors.

Proton Cancer Therapy

G. Kraft, Nucl. Phys. A 654 (1999) 1058c

Landau Distribution

- Bethe-Bloch describes mean energy loss

- Energy loss is distributes asymmetrically

- approximated by

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

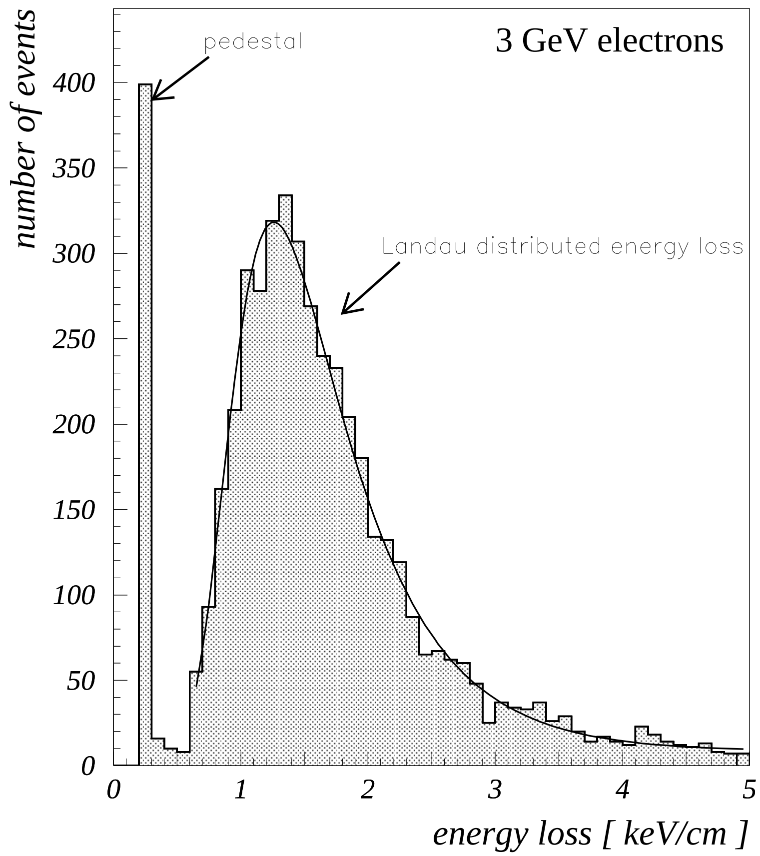
$$\lambda = \frac{\left(\frac{dE}{dx}\right) - \left(\frac{dE}{dx}\right)^{\text{m.p.}}}{0.123\,\text{keV}}$$

$\left(\frac{dE}{dx}\right)^{\text{m.p.}}$ most probable energy loss

- important in gases, thin absorbers

- Argon, $\beta\gamma = 4$:
  $\left(\frac{dE}{dx}\right)^{\text{m.p.}} = 1.2\,\text{keV/cm}$; $\langle\frac{dE}{dx}\rangle = 2.69\,\text{keV/cm}$

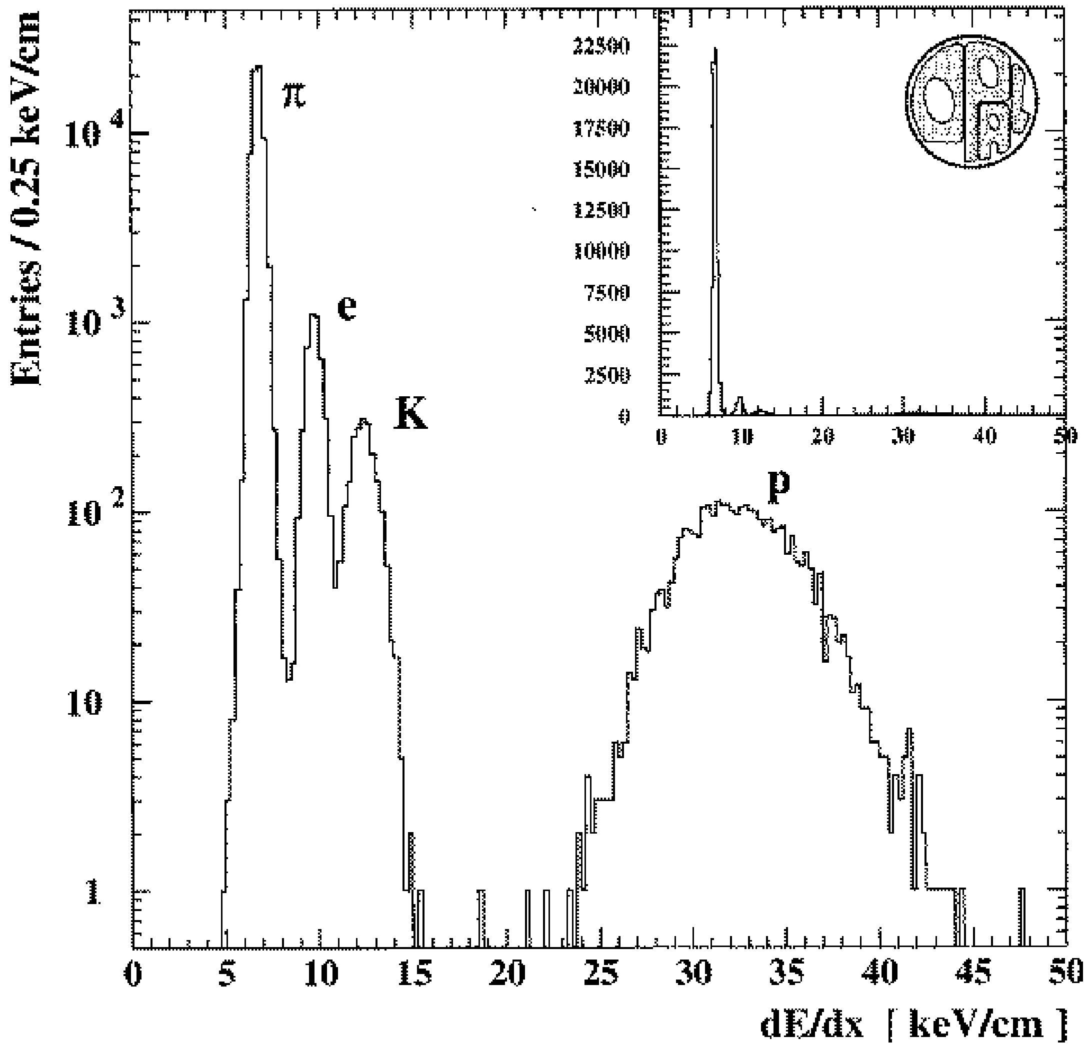
- For Particle Identification:
  - Measure often (typ. 160) to get distribution
  - Use “Truncated Mean”



Electrons in Ar:CH_4 (80:20)

K. Afforlderbach et al., Nucl. Instr. Meth. A410 (1998) 166

Particle Identification via dE/dx



Momentum interval $0.45\,\mathrm{GeV}/c - 0.48\,\mathrm{GeV}/c$

OPAL Collaboration, CERN-PPE-94-49

Scintillation

inorganic crystals
- effect of the lattice
- electron-hole pair creation, excitons
- de-excitation at activator centers
- NaI(TI); CsI(TI); BaF_2; BGO; ...

organic liquids or plastic
- three components
- primary scintillator: antracene $C_{14}H_{10}$;
  naphthalene $C_{10}H_8$; ...
- wavelength shifter: POPOP*; BBO$^\#$; ...
- base material: mineral oil; PMMA$^+$; ...

gases
- energy loss by excitation
- recombination
- Xe, Kr, Ar, N_2 ...

$*$	$C_{24}H_{16}N_2O_2$:	1.4-Bis-[2-(5-phenyloxazolyl)]-benzene
#	$C_{27}H_{19}NO$:	2.5-di-(4-biphenyl)-oxazole
+	$C_5H_8O_2$:	polymethylmetacralate

Organic Plastic Scintillator

Non-Linear light yield to Energy Loss:

$$N = N_0 \frac{dE/dx}{1 + k_B \cdot (dE/dx)}$$

$k_B \approx 0.01\,\mathrm{g/MeV\,cm^2}$ Birk's density Parameter

Recently better approximation, by A. Menchaca et al.

Typically $100\,\mathrm{eV}$ energy loss for one photon

wavelength shifting necessary to avoid self-absorption

Cherenkov Radiation

A charged particle with a velocity v larger than the velocity of light in a medium emits light (Pavel A. Cherenkov, Ilja M. Frank, Igor Y. Tamm, Nobel Price 1958)

Threshold: $$\beta_{\text{thres}} = \frac{v_{\text{thres}}}{c} \geq \frac{1}{n} \qquad \gamma_{\text{thres}} = \frac{n}{\sqrt{n^2 - 1}}$$

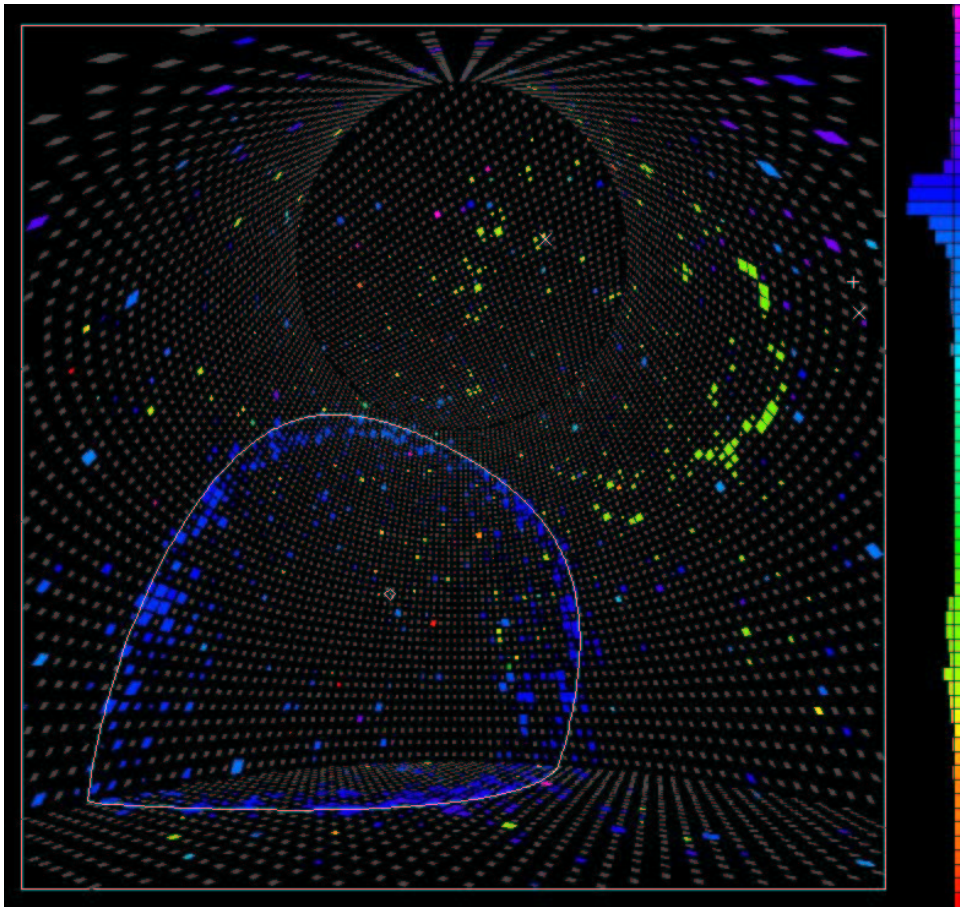
Angle of emission: $$\cos\theta_c = \frac{1}{\beta\, n} = \frac{1}{\frac{v}{c}\, n}$$

$$\theta_c^{\text{max}} = \arccos\frac{1}{n} \quad \text{Water: } \theta_c^{\text{max}} = 42^\circ \quad \text{Neon (1atm): } \theta_c^{\text{max}} = 11\,\text{mrad}$$

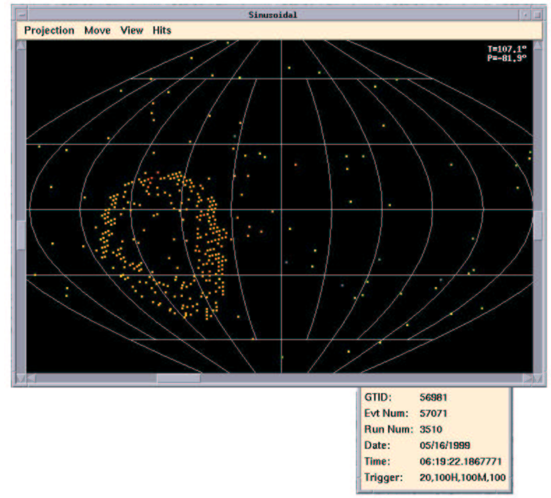
Number of photons: $$\frac{d^2N}{dEdl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

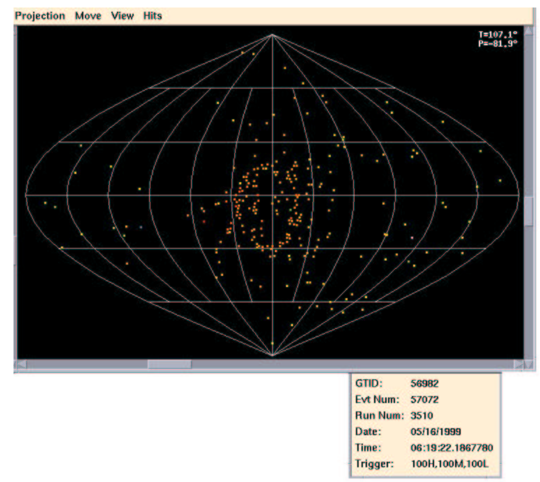
$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

Water Cherenkov



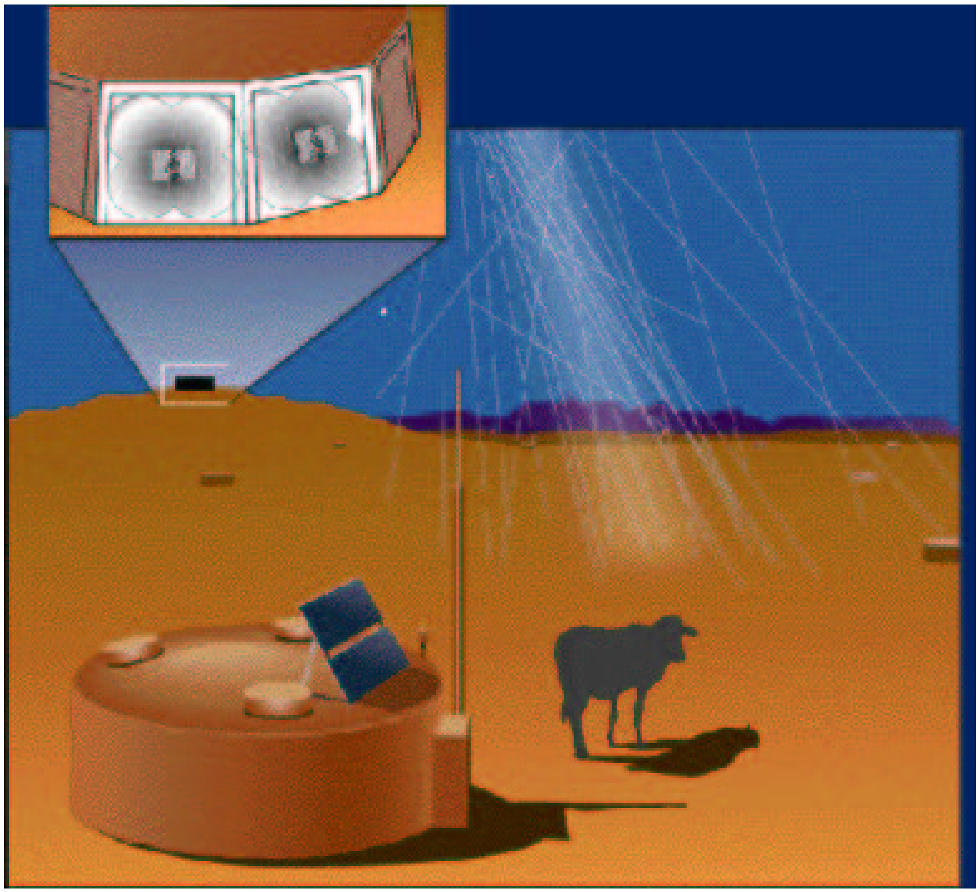
neutrino induced muon in SuperKamiokande

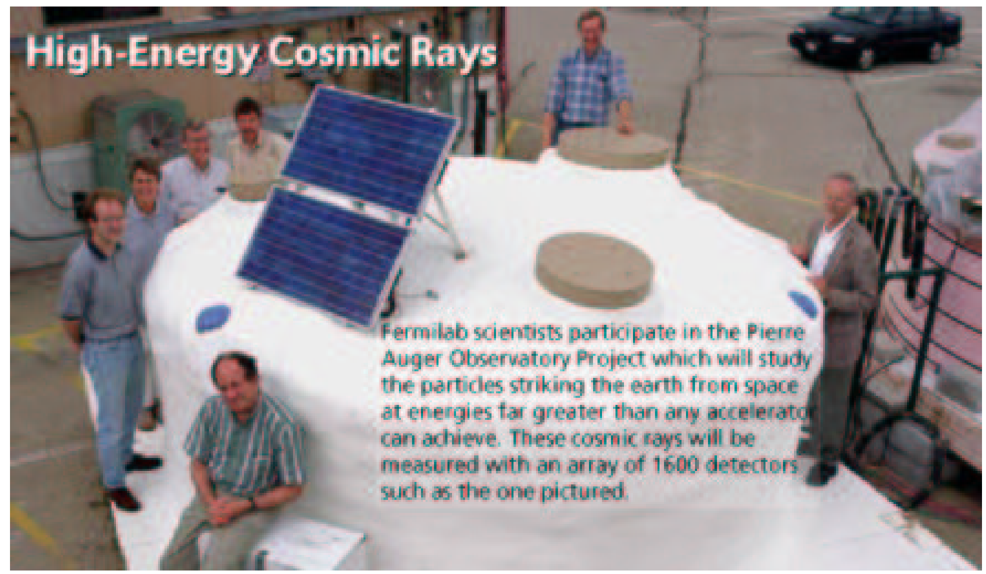




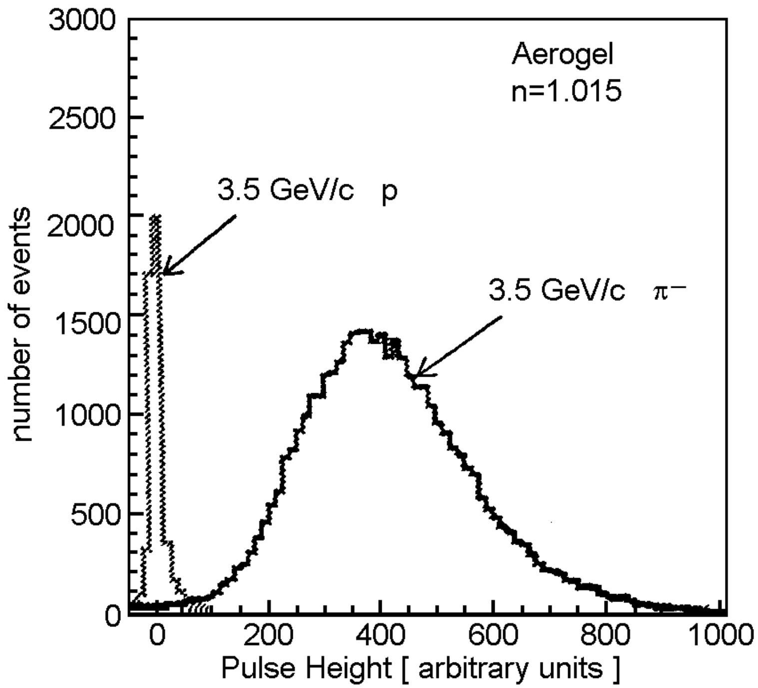
neutrino induced muon (top) and electron (bottom) in SNO

Auger Experiment: Water Cherenkov's





Threshold Cherenkov Detectors



Aerogel: $n = 1.015 \Rightarrow \gamma_{\text{thres}} = 5.84$

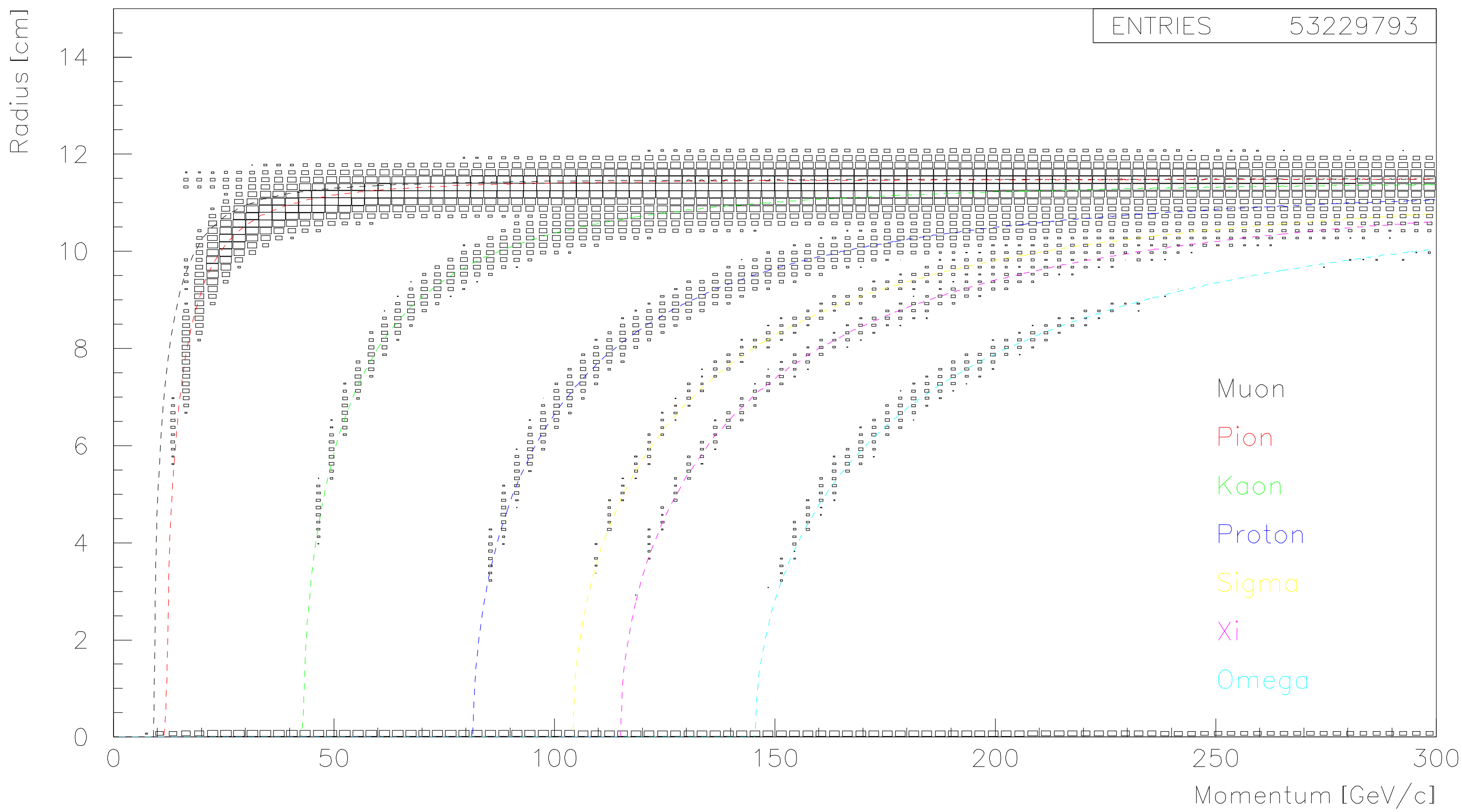
$3.5\,\text{GeV/c} \Rightarrow \gamma_\pi = 24.2, \quad \gamma_p = 2.86$

To identify more than 2 particles and/or to cover wider momentum range: Several counters at different thresholds

A. Satpathy et al., BELLE Collaboration, hep-ex/9903045

Ring Imaging Cherenkov Detectors

Measure Cherenkov angle, not only threshold



SELEX RICH, 53 Million single negative track events

J. Engelfried et al., Nucl. and Instr. and Methods A 502 (2003) 62-65

Transition Radiation Detectors (TRD)

Transition Radiation: Reformation of particle field while traveling from medium with $\epsilon = \epsilon_1$ to medium with $\epsilon = \epsilon_2$.

Energy of radiation emitted at a single interface

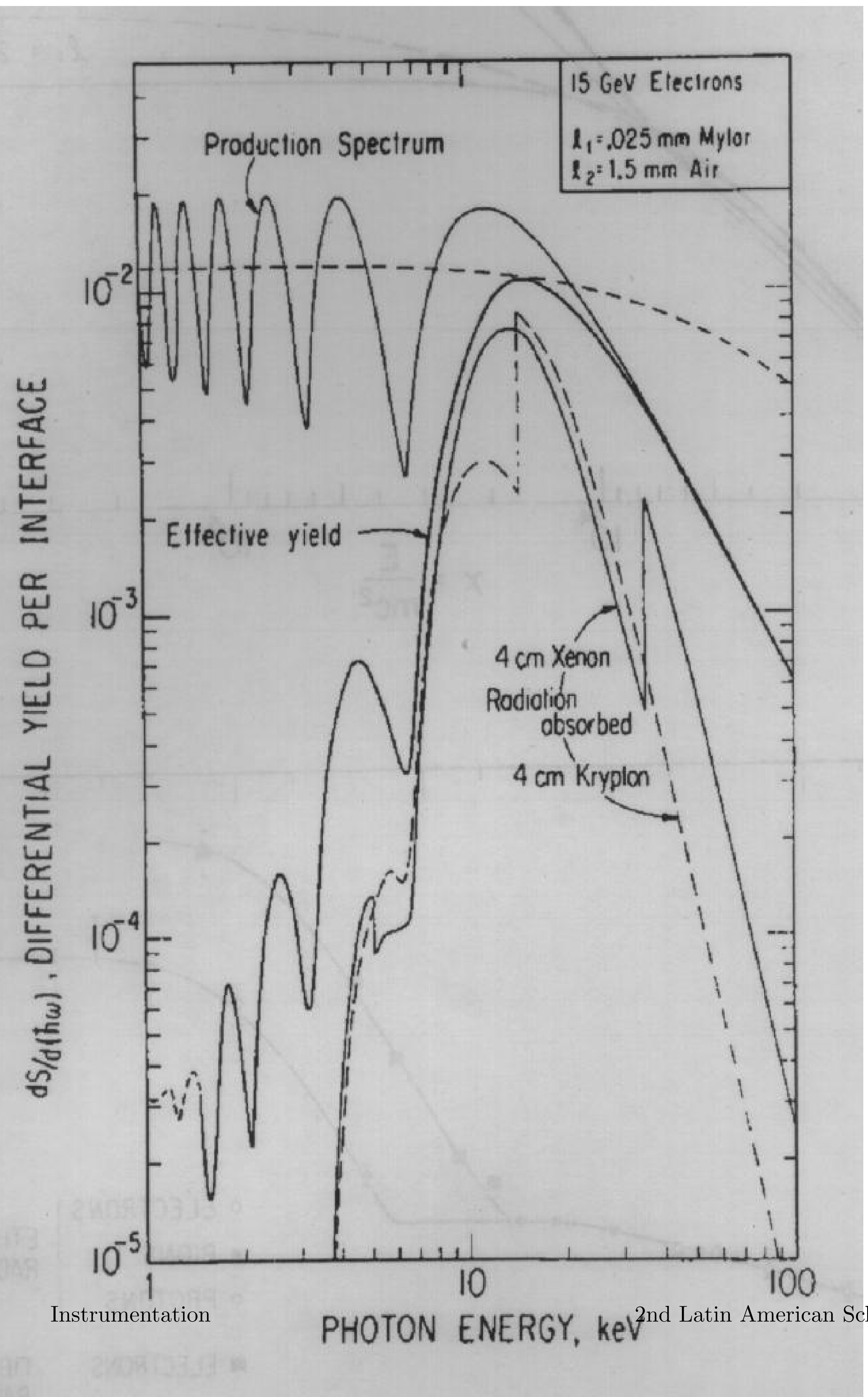
$$S = \frac{\alpha \hbar z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma$$

$\alpha = 1/137$, ω_1, ω_2 plasma frequencies, $\gamma = E/mc^2$.
Typical values: Air $\omega_1 = 0.7\,\mathrm{eV}$, polypropylene $\omega_2 = 20\,\mathrm{eV}$

Spectral and angular dependence of Transition Radiation:

$$\frac{d^2}{d\vartheta d\omega} = \frac{2e^2}{\pi c} \left(\frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_1^2/\omega^2} - \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_2^2/\omega^2} \right)^2$$

$\Longrightarrow$ Most of radiation in cone with half angle $1/\gamma$: forward in particle direction.



- Large photon energies $\omega > \gamma\omega_2 \approx 20 - 30\,\mathrm{KeV}$: large drop of intensity $\propto \gamma^4/\omega^4$
- Medium energies $\gamma\omega_1 < \omega < \gamma\omega_2$: Logarithmic decrease with ω
- Small energies $\omega < \gamma\omega_1 \approx 1\,\mathrm{KeV}$: intensity almost constant

Probability to emit a KeV photon: $\approx 10^{-2} \Longrightarrow$ Need a lot of interfaces: stack of radiator foils.
Consequences:

- Need minimum foil thickness so particle field reaches new equilibrium
- Transition $\omega_1 \rightarrow \omega_2$ and $\omega_2 \rightarrow \omega_1$ equal $\Longrightarrow$ Interference effects (min and max in fig)
- Equally spaced foils: Interference between amplitude of different foils
- Finite thickness of foils: re-absorption of radiation ($\propto Z^5$): Low Z materials.

Typical values used in TRDs:
Thickness: $30\,\mu$m, distance: $300\,\mu$m,
materials: mylar, CH_2, carbon fibers, lithium.

Detection of Transition Radiation

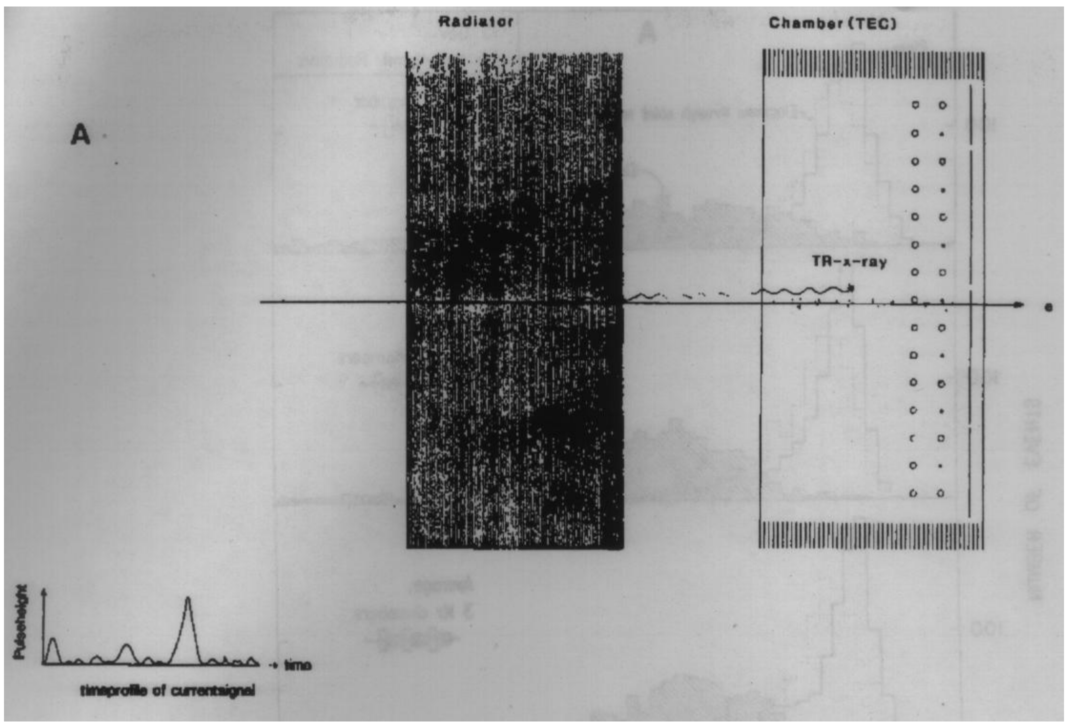
X-rays emitted under small angle to particle track

$\Longrightarrow$ X-ray detector sees X-rays and particle dE/dx together.

Typical dE/dx in gas detectors: some KeV/cm and Landau distributed

$\Longrightarrow$ Signals from dE/dx and X-ray similar

Detector: Use "thin" MWPC, with Xenon or Krypton, several (10) radiator / chamber units to beat Landau



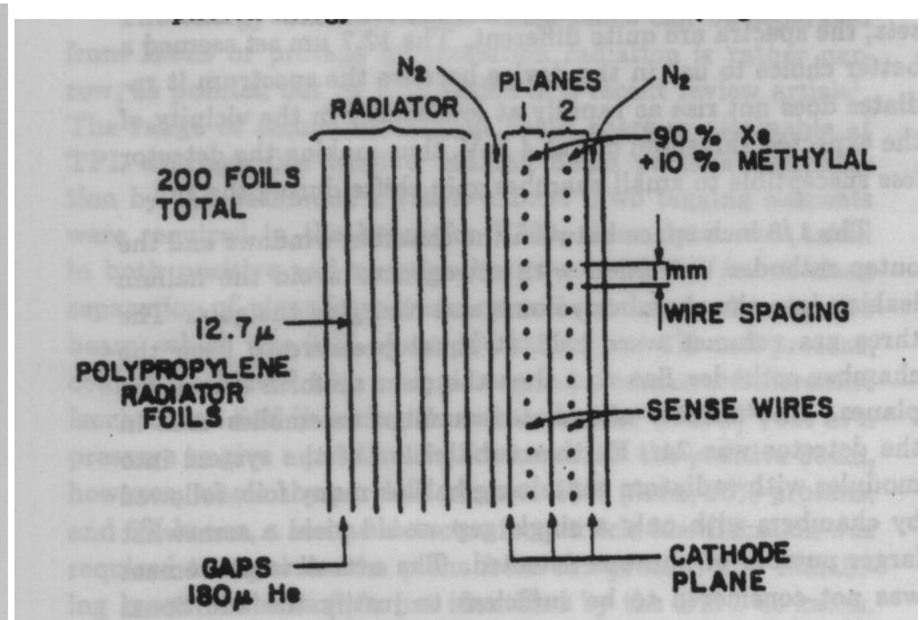
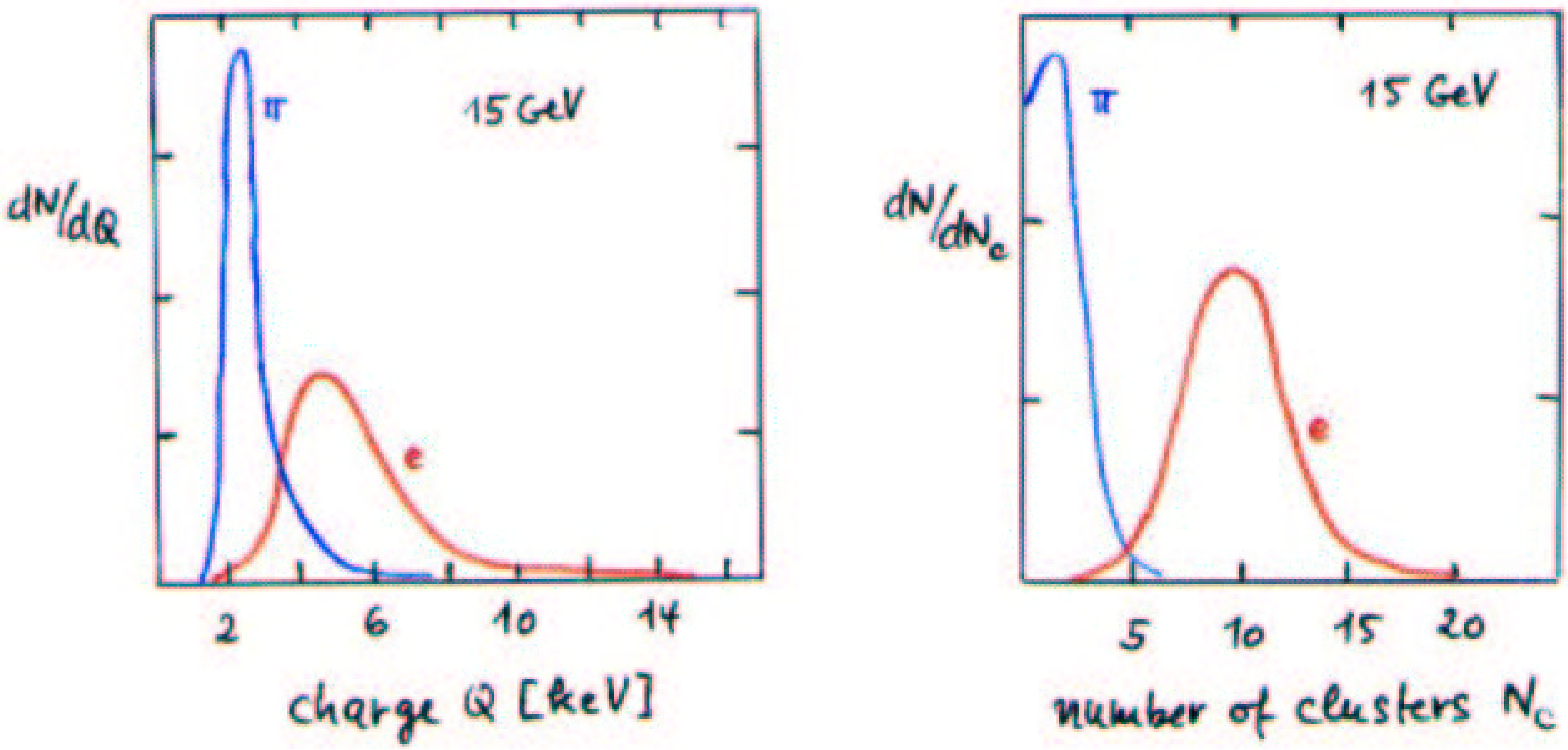
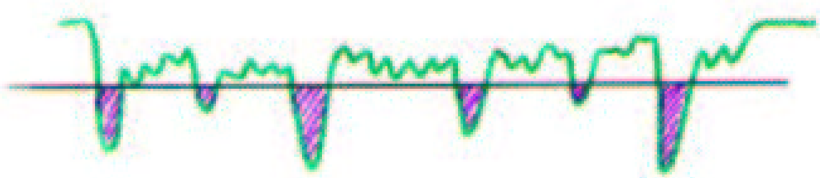


Fig **4. Schematic of a radiator-chamber module showing the final design parameters discussed in the text.**

Two identification methods: Charge integration, Cluster counting





Li-foils as radiator

Fabjan et al. 1980

40

Bremsstrahlung

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{PDG: } X_0 = \frac{716.4\,A}{Z(Z+1)\ln(287/\sqrt{Z})}\,[\mathrm{g/cm^2}]$$

$$\frac{dE}{dx} \propto E \Rightarrow \qquad \text{Critical Energy } \frac{dE}{dx}\Big|_{\text{ion}} = \frac{dE}{dx}\Big|_{\text{brems}}$$

$$E^e_{\text{crit}} = \begin{cases} \frac{610\,\mathrm{MeV}}{Z+1.24} & \text{for solids and liquids} \\ \frac{710\,\mathrm{MeV}}{Z+0.92} & \text{for gases} \end{cases}$$

Bremsstrahlung (cont.)

Material	$X_0\,[\mathrm{g/cm^2}]$	$X_0\,[\mathrm{cm}]$	$E^e_{\mathrm{crit}}\,[\mathrm{MeV}]$
air	37	30000	84
iron	13.9	1.76	22
lead	6.4	0.56	7.3

$$-\frac{dE}{dx} \propto \frac{1}{m^2} \Rightarrow \text{Electron Bremsstrahlung dominates}$$

But: Muons in iron: $E^{\mu}_{\mathrm{crit}} = E^{e}_{\mathrm{crit}} \left(\frac{m_\mu}{m_e}\right)^2 = 960\,\mathrm{GeV}$

$\Rightarrow$ Muon Calorimetry at TeV Energies

Bremsstrahlung important for electromagnetic cascades (Calorimetry)

Direct Electron Pair Production

in Coulomb field of Nucleus via virtual photons

$$-\frac{dE}{dx}\Big|_{\text{pair}} \propto E \quad \text{for large E}$$

$$-\frac{dE}{dx} = a(E) + b(E)E$$

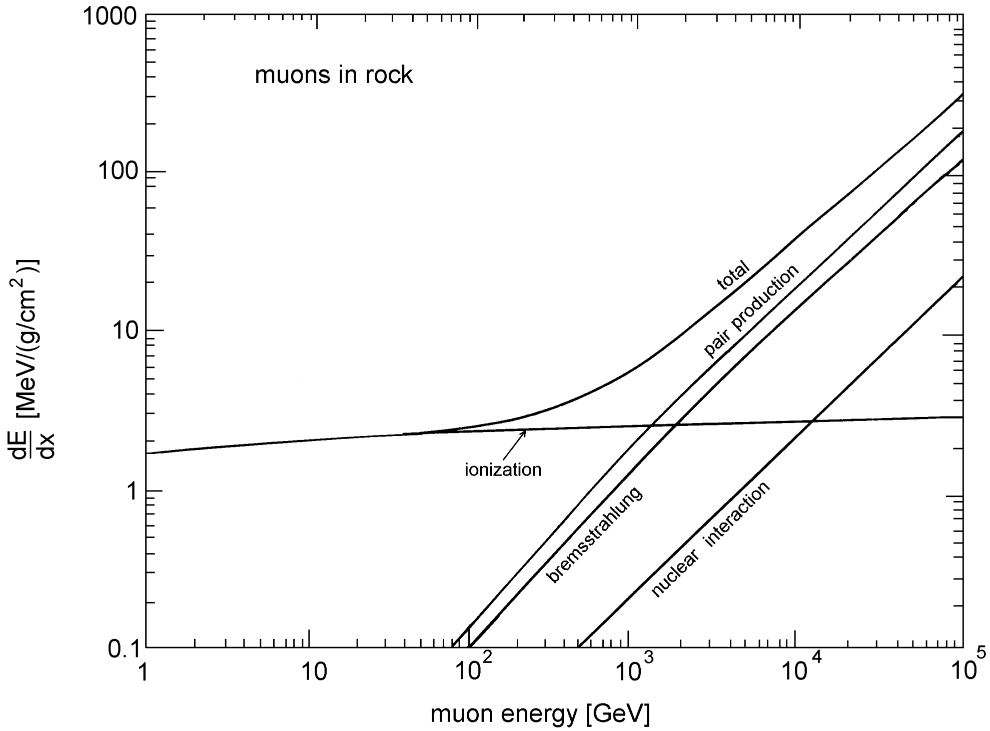
$a(E)$ – Ionization energy loss

$b(E) = b_{\text{brems}}(E) + b_{\text{pair}}(E) + b_{\text{nucl.int.}}(E)$

Range of muons

$$R = \int_E^0 \frac{dE}{-dE/dx} = \frac{1}{b}\ln(1 + \frac{b}{a}E)$$

$$R = \begin{cases} 140\,\text{m} \quad \text{rock for } E = 100\,\text{GeV} \\ 800\,\text{m} \quad \text{rock for } E = 1\,\text{TeV} \\ 2300\,\text{m} \quad \text{rock for } E = 10\,\text{TeV} \end{cases}$$



Energy loss of muons in Rock
$(Z = 11,\ A = 22;\ \rho = 3\,\text{g/cm}^2)$

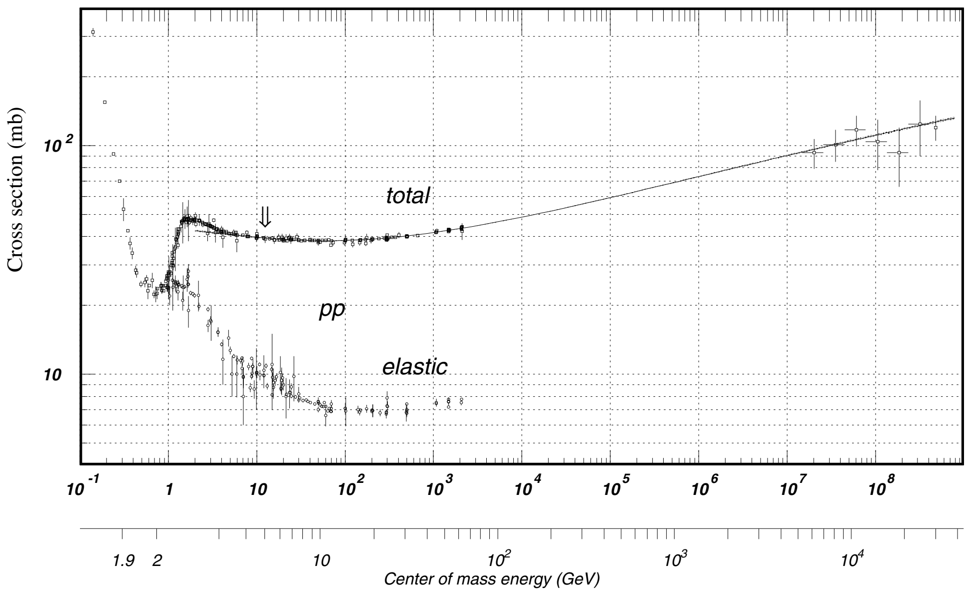
Nuclear Interactions

Important for the detection of neutral particles

$\sigma_{\text{tot}} \approx 50\,\text{mbarn} \qquad \sigma_{\text{inel}} \propto A^{\alpha}, \alpha = 0.71$

Nuclear Interaction length $\quad \lambda_I = \dfrac{A}{N_A\,\rho\,\sigma_{\text{tot}}}$

Nuclear Absorption length $\quad \lambda_a = \dfrac{A}{N_A\,\rho\,\sigma_{\text{inel}}}$



for most material $\lambda_I, \lambda_a > X_0$

	Al	Fe	Pb	air
λ_I [cm]	26.2	10.6	10.4	48000
λ_I [g/cm]	70.6	82.8	116.2	62.0

Multiplicity grows logarithmically with E,
Average $p_T = 350\,\text{MeV}/c$

Outline of first part of lecture

- Introduction, Kinematics
- Interaction of Charged Particles
  - Ionization, scintillation, Cherenkov and Transition Radiation
  - Bremsstrahlung and nuclear interactions
- Interaction of Neutral Particles
  - photons: photoelectric effect, Compton scattering, pair production
  - neutrons
  - neutrinos
- Electromagnetic Showers
- Hadron Showers

Interactions of Photons – Introduction

Photons are attenuated in matter.

$$I = I_0 \, e^{-\mu x}$$

μ Mass Attenuation Coefficient

$$\mu = \frac{N_A}{A} \sum_{i=1}^{3} \sigma_i$$

$$\sigma_i = \begin{cases} i = 1\text{: Photoelectric Effect} \\ i = 2\text{: Compton Scattering} \\ i = 3\text{: Pair Production} \end{cases}$$

Photoelectric Effect

$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$ predominantly in K-shell

Complicated energy and Z dependence

$$\sigma^{K}_{\text{photo}} = \left(\frac{32}{\epsilon^7}\right)^{1/2} \alpha^4 \, Z^5 \, \sigma_{\text{Thomson}} \quad [\text{cm}^2/\text{atom}]$$

$$\epsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma_{\text{Thomson}} = \frac{8}{3}\pi \, r_e^2 = 665\,\text{mbarn}$$

For high energies:

$$\sigma^{K}_{\text{photo}} = 4\pi \, r_e^2 \, Z^5 \, \alpha^4 \, \frac{1}{\epsilon}$$

Compton Scattering

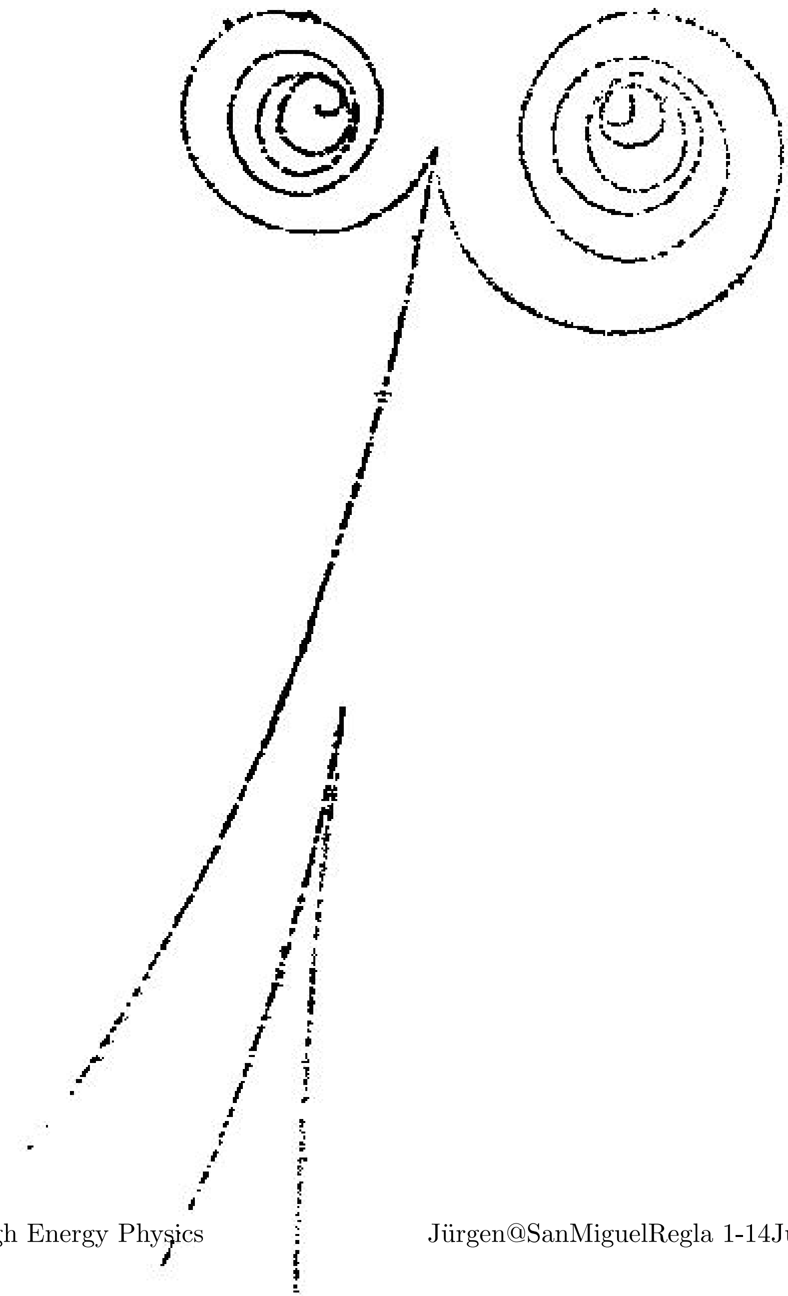
$$\gamma + e \rightarrow \gamma' + e'$$

at high energies: $\sigma_C \propto \frac{\ln \epsilon}{\epsilon} \cdot Z$

$$\frac{E'_\gamma}{E_\gamma} = \frac{1}{1 + \epsilon(1 - \cos\theta_\gamma)}$$

$$E_{\text{kin}}^{\text{max}}(\theta_\gamma = \pi) = \frac{2\epsilon^2}{1 + 2\epsilon} m_e c^2 \quad \text{for } \epsilon \gg 1 \;\; E_{\text{kin}}^{\text{max}}(\theta_\gamma = \pi) \rightarrow E_\gamma$$

Pair Production



$$\gamma + \text{nucleus} \longrightarrow \text{nucleus}' + e^+ + e^-$$

threshold energy:

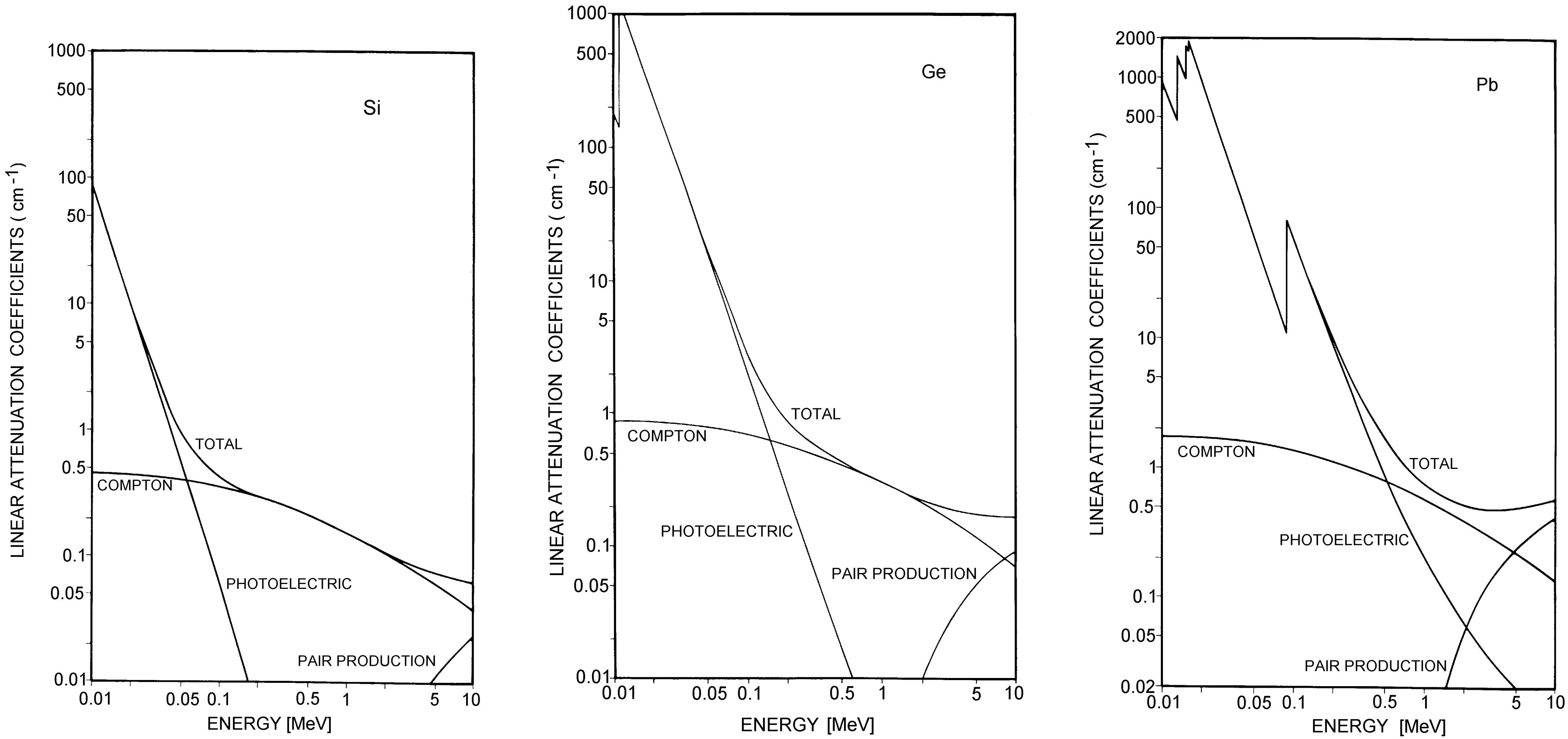
$$E_\gamma \geq 2\, m_e c^2 + \frac{2\, m_e c^2}{m_{\text{target}}} = \begin{cases} \approx 2\, m_e c^2 & \text{on a nucleus} \\ 4\, m_e c^2 & \text{on an electron} \end{cases}$$

Cross section for $E_\gamma \gg 20\,\text{MeV}$

$$\sigma_{\text{pair}} = 4\,\alpha\, r_e^2\, Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \quad [\text{cm}^2/\text{atom}]$$

$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

Mass Attenuation Coefficients (μ)



Interaction of Neutrons

indirect technique: neutrons interact and produce charged particles

- Low Energies ($< 20\,\mathrm{MeV}$):
  $n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} \quad \Rightarrow$ LiI(Tl) scintillators
  $n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} \quad \Rightarrow$ BF_3 gas counters
  $n + {}^{3}\mathrm{He} \rightarrow p + {}^{3}\mathrm{H} \quad \Rightarrow$ ^{3}He-filled proportional counters
  $n + p \rightarrow n + p \quad \Rightarrow$ proportional chambers with for example CH_4

- High Energies ($E > 1\,\mathrm{GeV}$)
  $n + {}^{235}\mathrm{U} \rightarrow$ fission products $\quad \Rightarrow$ coated proportional counters
  $n +$ nucleus $\rightarrow$ hadron cascade $\quad \Rightarrow$ calorimeters

Interactions of Neutrinos

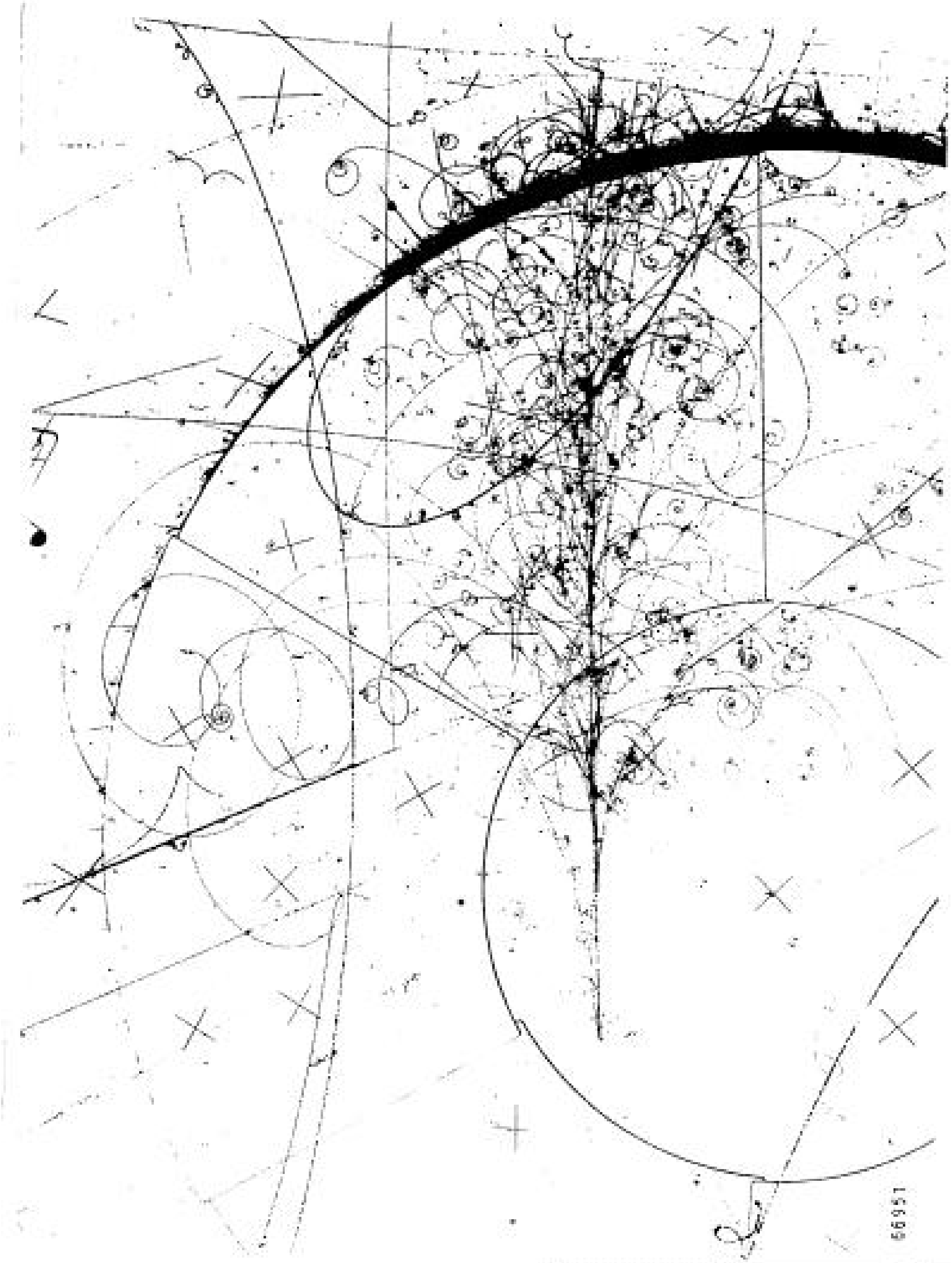
$$\begin{aligned} \nu_e + n &\rightarrow p + e^- & \bar{\nu}_e + p &\rightarrow n + e^+ \\ \nu_\mu + n &\rightarrow p + \mu^- & \bar{\nu}_\mu + p &\rightarrow n + \mu^+ \\ \nu_\tau + n &\rightarrow p + \tau^- & \bar{\nu}_\tau + p &\rightarrow n + \tau^+ \end{aligned}$$

Small cross section: (MeV range): $\sigma(\nu_e N) = \frac{4}{\pi} \cdot 10^{-10} \left(\frac{\hbar p}{(m_p c)^2} \right)^2 = 1.6 \cdot 10^{-44}\,\mathrm{cm}^2$ for $0.5\,\mathrm{MeV}$

for high Energies (GeV range):

$$\sigma(\nu_\mu N) = 0.67 \cdot 10^{-38}\, E_\nu\, \mathrm{cm}^2/(\mathrm{nucleon\ GeV})$$
$$\sigma(\bar{\nu}_\mu N) = 0.34 \cdot 10^{-38}\, E_\nu\, \mathrm{cm}^2/(\mathrm{nucleon\ GeV})$$

- Indirect Measurement by missing momentum and missing energy technique



$$\nu_e + \text{nucleon} \rightarrow e^- + \text{hadron}$$

Electromagnetic shower

Electromagnetic Cascades (Showers)

Photon $\longrightarrow$ Pair Production   Electron / positron $\longrightarrow$ Bremsstrahlung (Photon)

- Simple Model, measured in "steps" t (one conversion, related to Radiation length X_0):
  Number of Particles: $N(t) = 2^t$
  Energy of particles: $E(t) = E_0 \cdot 2^{-t}$
  Multiplication stops if $E(t) < E_c$ $E_c = E_0 \cdot 2^{-t_{\max}}$ $E_c :\approx$ Pair production threshold

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \propto \ln E_0$$ position of shower maximum

Total number of shower particles:

$$S = \sum_{t=0}^{t_{\max}} N(t) = \sum 2^t = 2^{t_{\max}+1} - 1 \approx 2 \cdot 2^{t_{\max}} = 2 \cdot \frac{E_0}{E_e} \propto E_0$$

Electromagnetic Showers (cont.)

Total track length (sampling step t, measures in units of X_0)

$$S^\star = \frac{S}{t} = 2 \cdot \frac{E_0}{E_c} \cdot \frac{1}{t}$$

$$\text{Energy Resolution} \quad \frac{\sigma(E_0)}{E_0} = \frac{\sqrt{S^\star}}{S^\star} = \frac{\sqrt{t}}{\sqrt{2E_0/E_c}} \propto \frac{\sqrt{t}}{\sqrt{E_0}}$$

Realistic description of longitudinal shower development:

$$\frac{dE}{dt} = \text{const} \cdot t^a \cdot e^{-bt} \qquad (a, b \text{ -- fit parameter})$$

Lateral spread, caused by multiple scattering:

$$\text{Molière Radius} \quad R_m = \frac{21\,\text{MeV}}{E_c} X_0[\text{g/cm}^2]$$

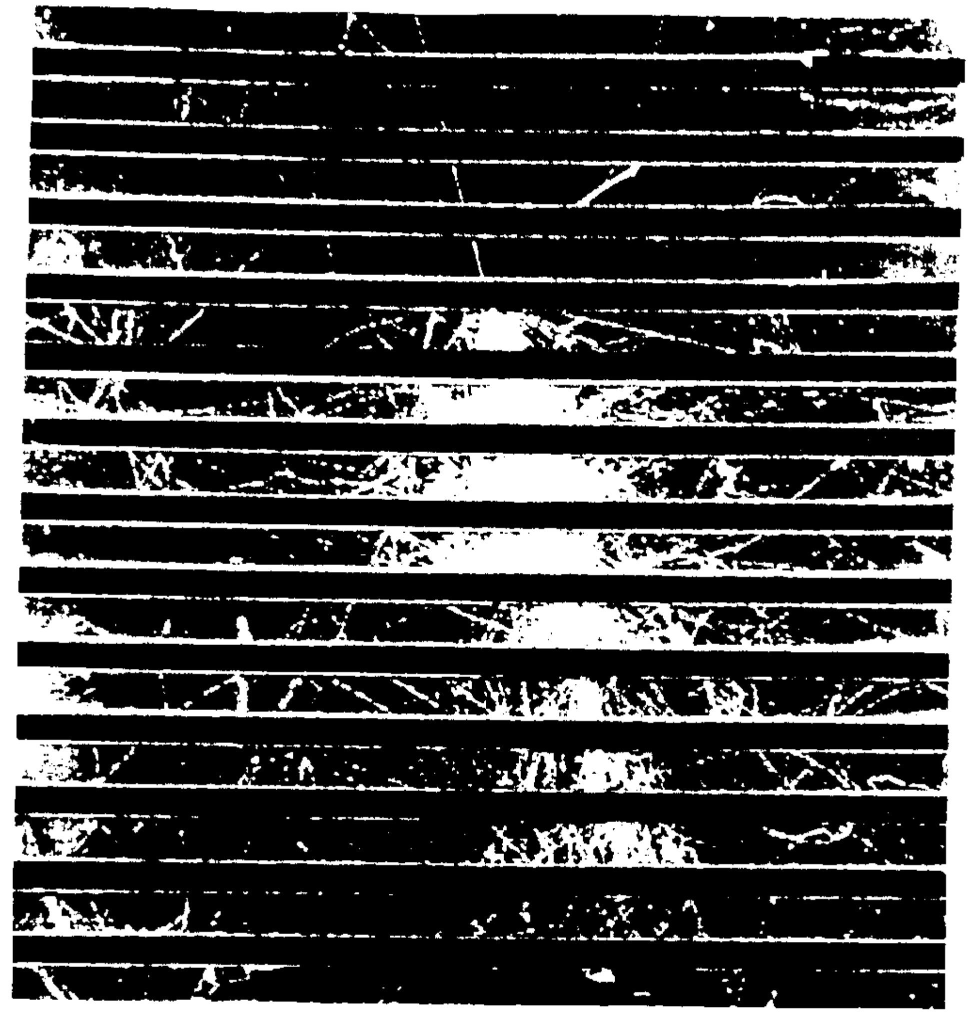
95 % of shower energy is contained in a cylinder of radius $2\,R_m$

$$\text{for homogeneous calorimeters:} \quad R_m = \begin{cases} \text{Fe:} \quad 14\,\text{g/cm}^2 \triangleq 1.8\,\text{cm} \\ \text{Pb:} \quad 18\,\text{g/cm}^2 \triangleq 1.6\,\text{cm} \end{cases}$$

$$\mu^- + \text{nucleus} \rightarrow \mu^- + \text{nucleus}' + \gamma$$

$$\gamma \rightarrow \text{electromagnetic shower}$$

Multiplate Cloud Chamber

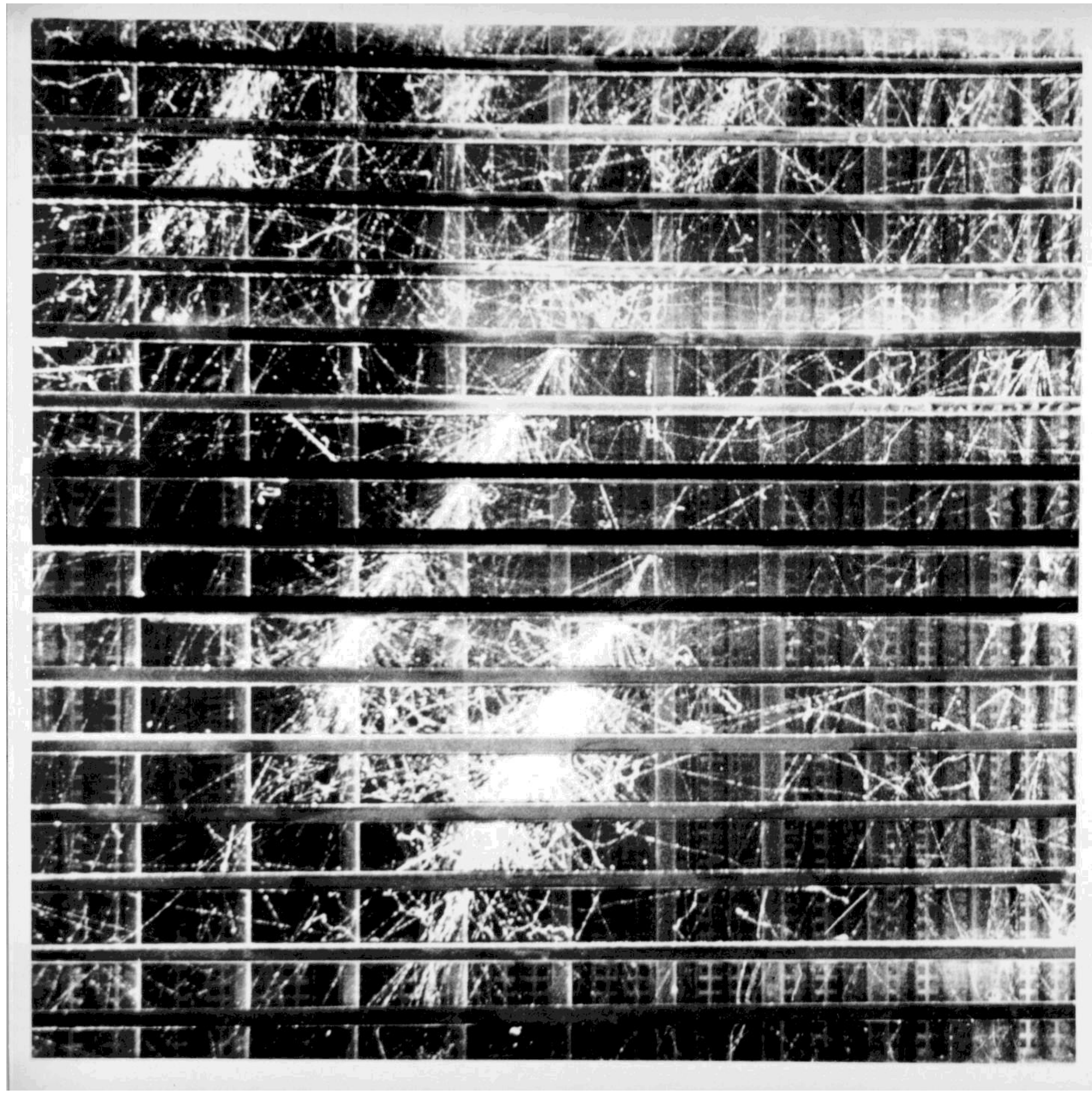


G.D. Rochester, K.E Turvey, Contemp. Phys. 22 (1981) 425

Air shower experiment

Multiplate Cloud Chamber below 3 m of concrete

Electromagnetic showers initiated by muon Bremsstrahlung



Hadron Showers

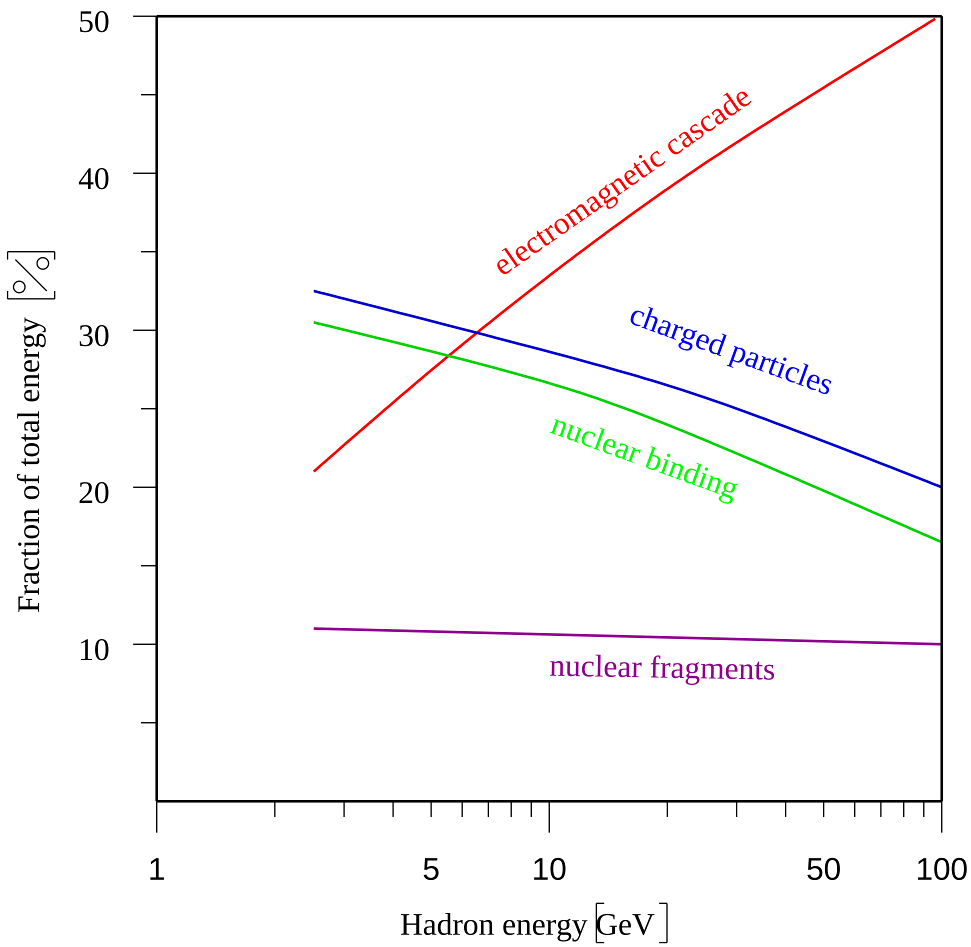
Longitudinal development: governed by nuclear interaction length λ_I
Lateral development: transverse momentum p_T of particles
since $\lambda_I > X_0$ and $\langle p_T \rangle \gg \langle p_T \rangle^{\text{mult. scatt.}}$
$\Rightarrow$ hadron showers are wider and longer than electromagnetic showers

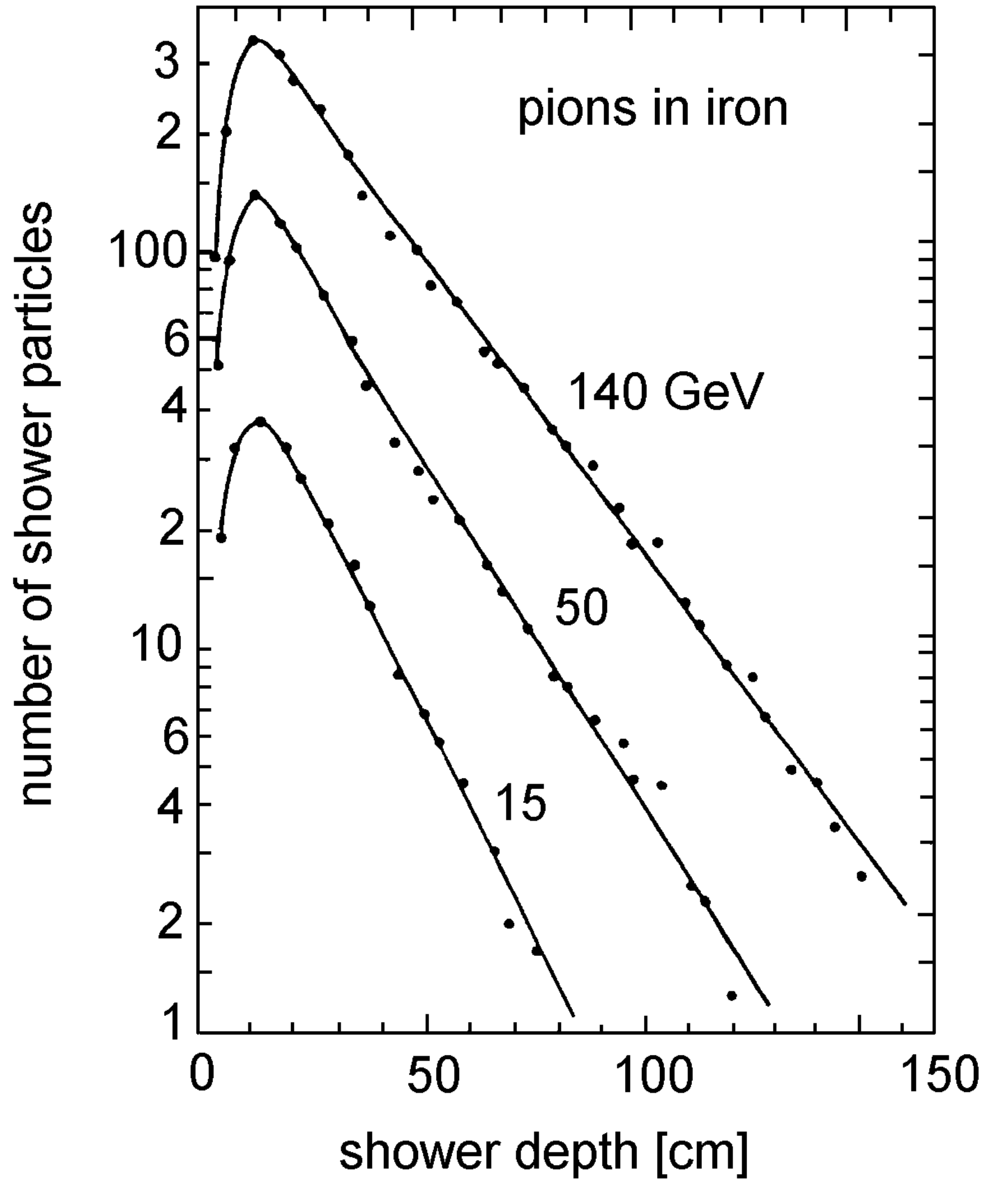
$$\text{Hadron Energy} \Rightarrow \begin{cases} \text{charged particles } (\mu\text{'s are lost}) \\ \text{electromagnetic showers via } \pi^0\ (e, \gamma; \text{ contained}) \\ \text{nuclear binding energy (can be partially recovered)} \\ \text{nuclear fragments (partially lost)} \end{cases}$$

$\Rightarrow$ Visible energy systematically lower

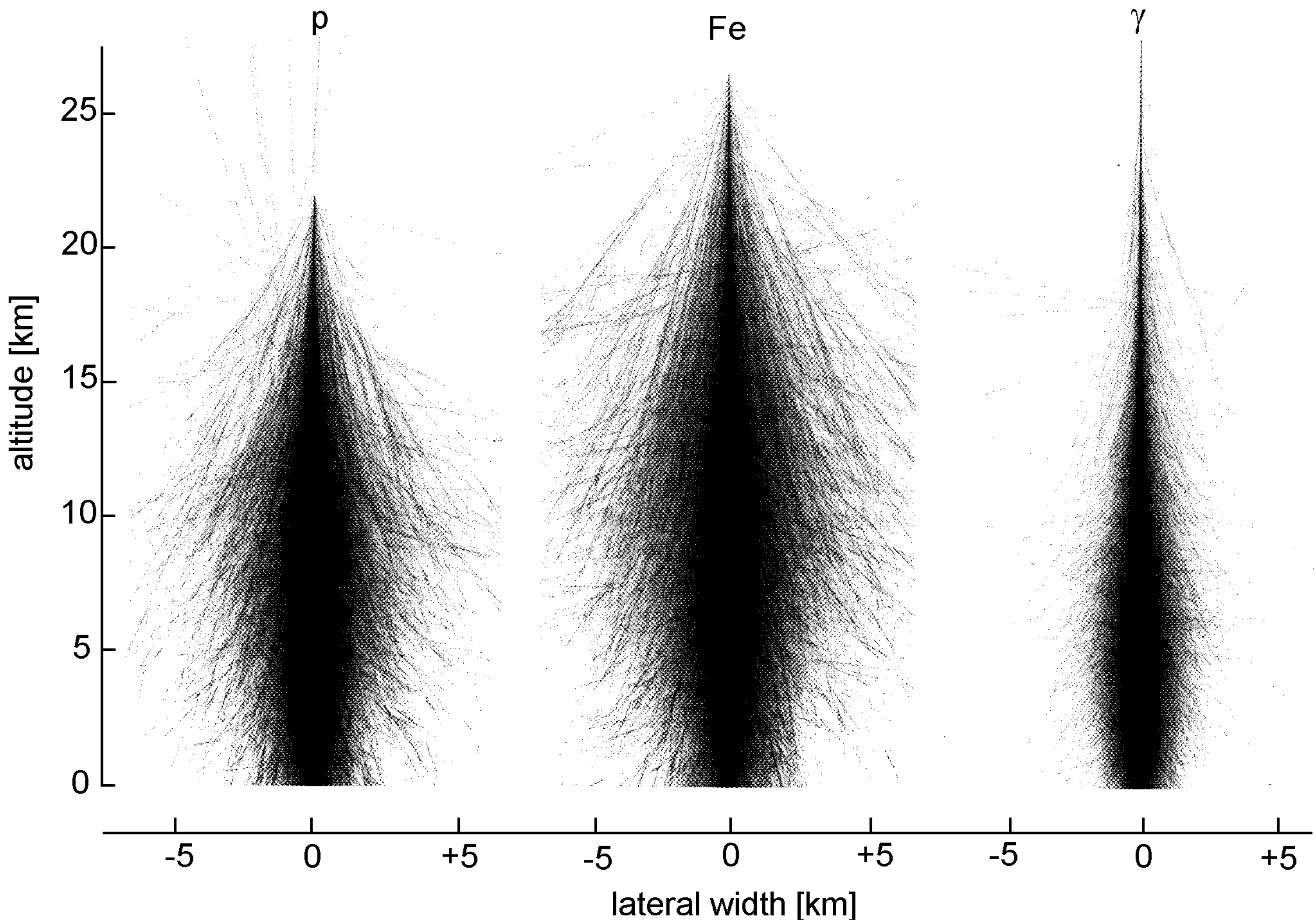
$\Rightarrow$ Due to fluctuations in energy losses Energy resolution is worse than for electromagnetic calorimeters

Problem of compensation: different response to electrons and hadrons. Need to balance to $e/\pi = 1$





M. Holder et al., Nucl. Instr. Meth. 151 (1978) 69

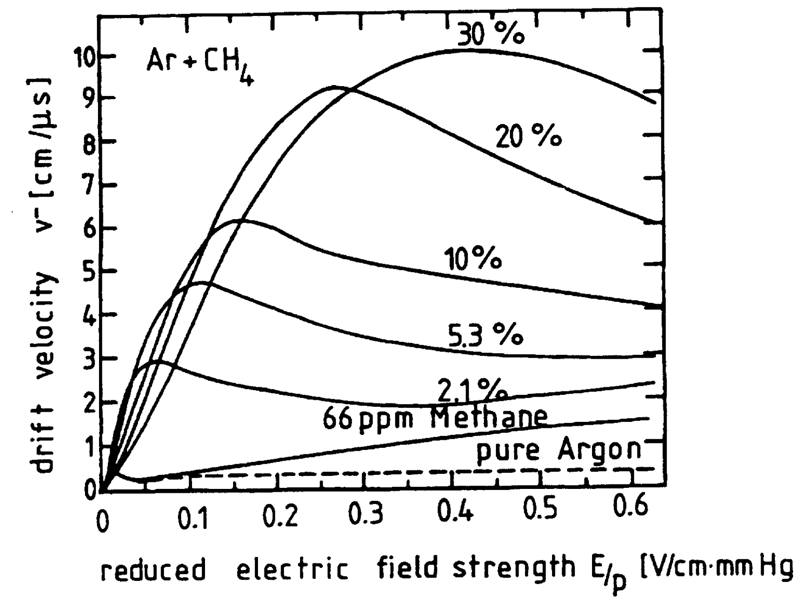


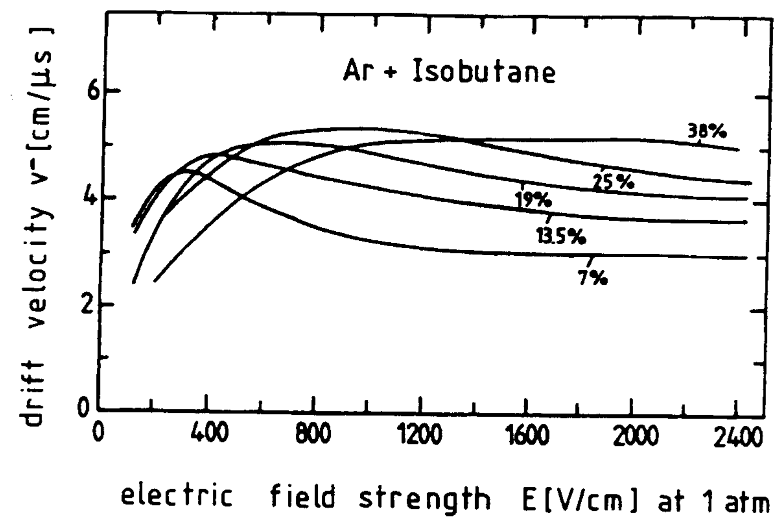
Extensive Air Showers, 10^{14} eV

J. Knapp, D. Heck, (1998)

Drift and Diffusion in Gases

- Electrons and Ions lose Energy by multiple collisions: $\rightarrow$ Thermalization
- Ionization diffuses (Gaussian) Width $\propto \sqrt(t)$
- With electric field:
  Drift with constant velocity v_{drift}
  In argon-isobutane: Typical $v_{\text{drift}}^{\text{electron}} \approx 5\,\text{cm}/\mu\text{sec}$
  Longitudinal and transverse diffusion different
  $(\sigma = \sigma(E_e))$
- $v_{\text{drift}} \propto 1/m$: Ions $> 10^3$ times slower!
- With additional magnetic field:
  drift under angle (Lorentz force)





Outline of first part of lecture (reminder)

- Introduction
- Interaction of Charged Particles
  - Ionization, scintillation, Cherenkov and Transition Radiation
  - Bremsstrahlung and nuclear interactions
- Interaction of Neutral Particles
  - photons: photoelectric effect, Compton scattering, pair production
  - neutrons
  - neutrinos
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End of First Part

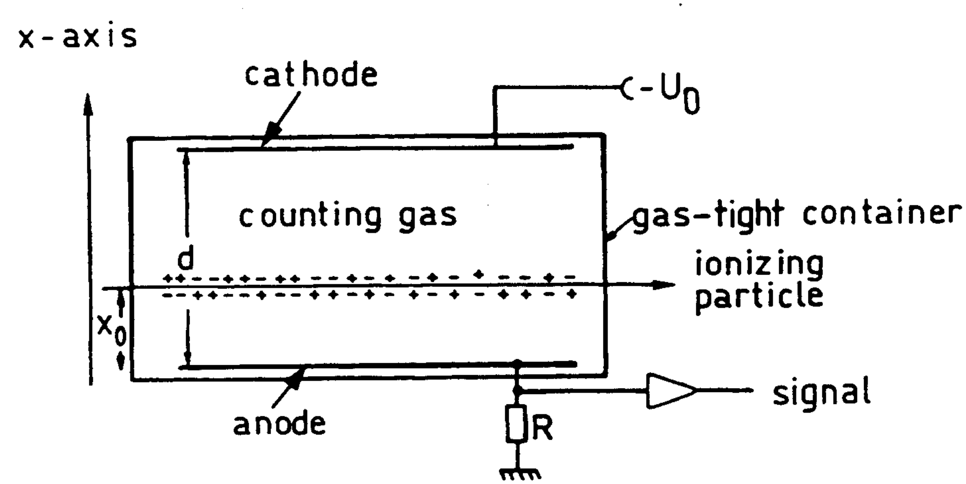
Second Part: Basic Design of Detectors

- Wire Chambers (in several incarnations): Position Measurement
- Calorimeters: Energy Measurement
- Particle Identification

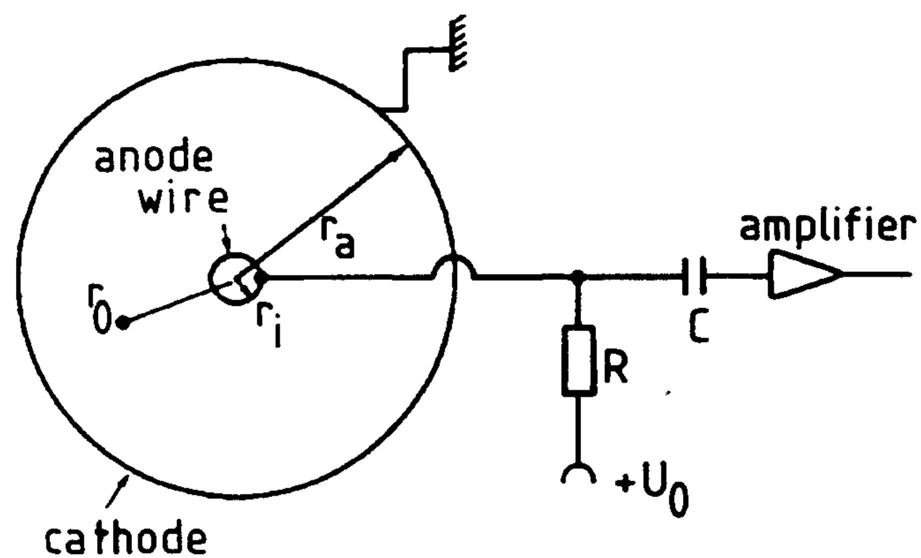
Note: Not always possible to classify detectors into one single group. Overlaps are common.

Ionization Chamber

- simplest Gas Detector
- Basically a Capacitor
- Also possible with liquids and solids



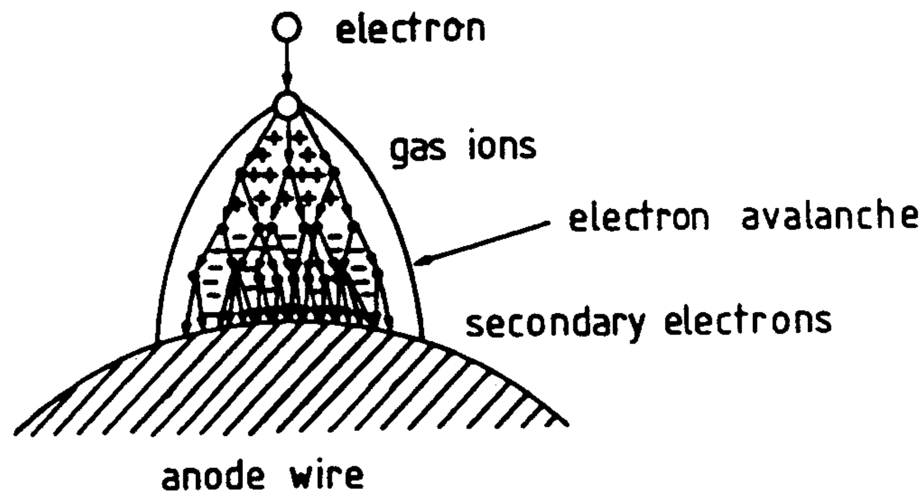
- Ionization (electrons and ions) drift to anode and cathode



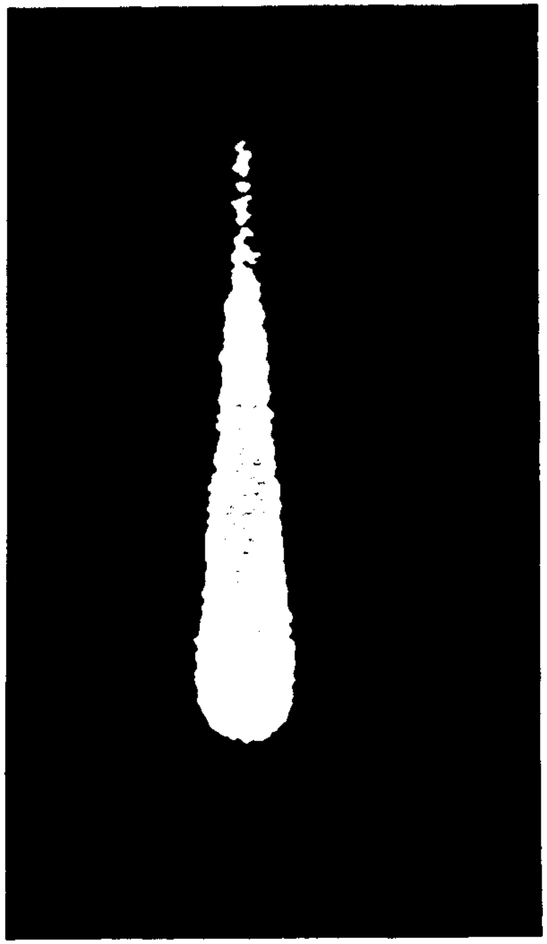
If time constant of RC is large enough: Integrated signal $\propto$ Ionization loss

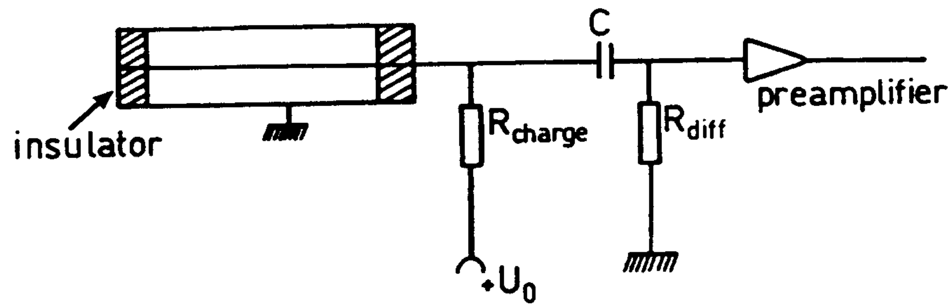
Proportional Counters

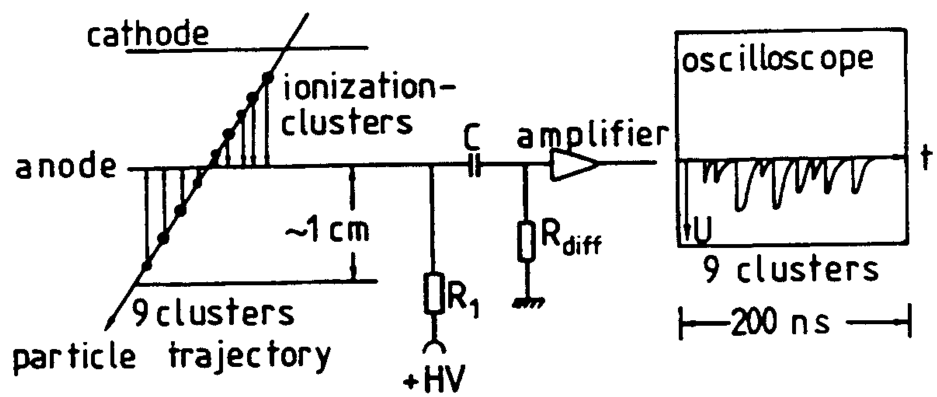
- Like Ionization chamber, but smaller wire and/or higher voltage
- Charge multiplication close to wire ($E \propto 1/r$)
- Electrons gain enough energy between collisions to ionize themselves.



- Proportional: Gas amplification constant
  $\rightarrow$ Signal $\propto$ primary ionization

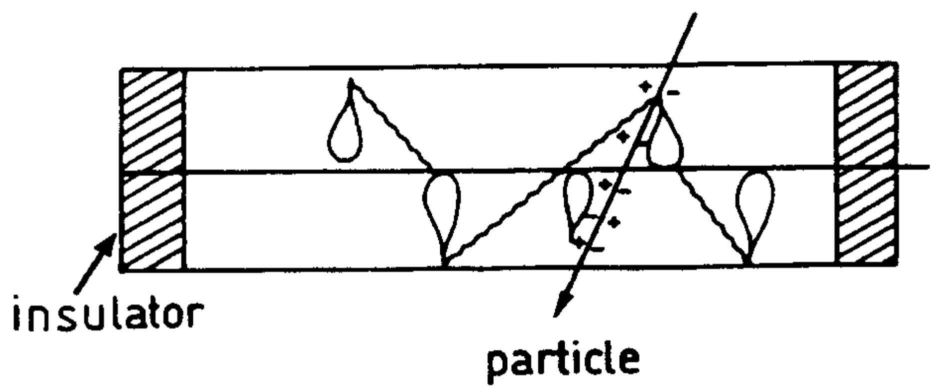



C
preamplifier
insulator
R charge
R diff
+U0


cathode
ionization-
clusters
anode
C
amplifier
oscilloscope
t
U
~1 cm
R diff
R1
+HV
9 clusters
particle trajectory
9 clusters
200 ns

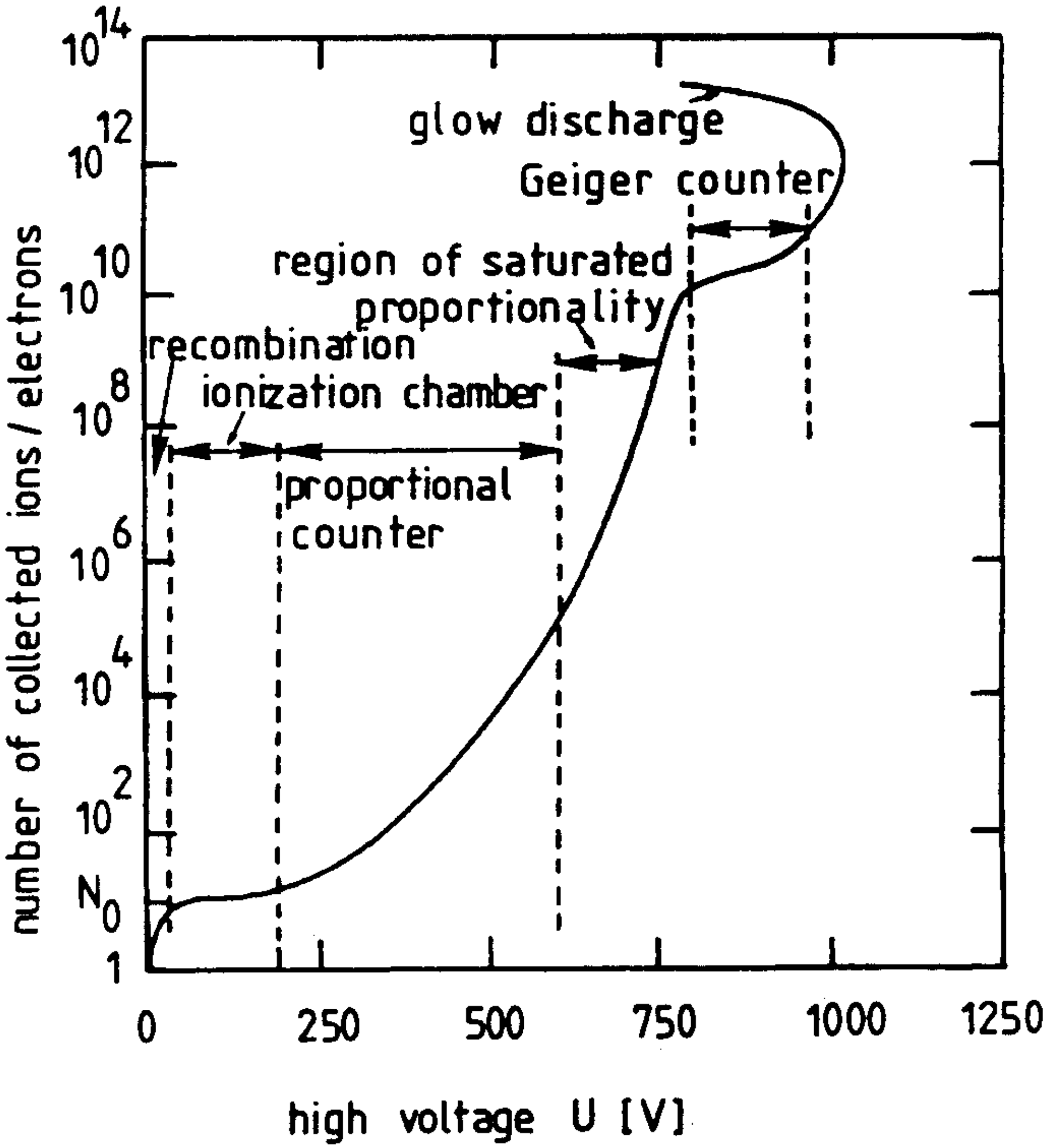
Geiger-Müller Counter

- Even higher voltage
- Copious production of photons in avalanche
- Photons make more ionization by photoelectric effect
- Also far away from original avalanche



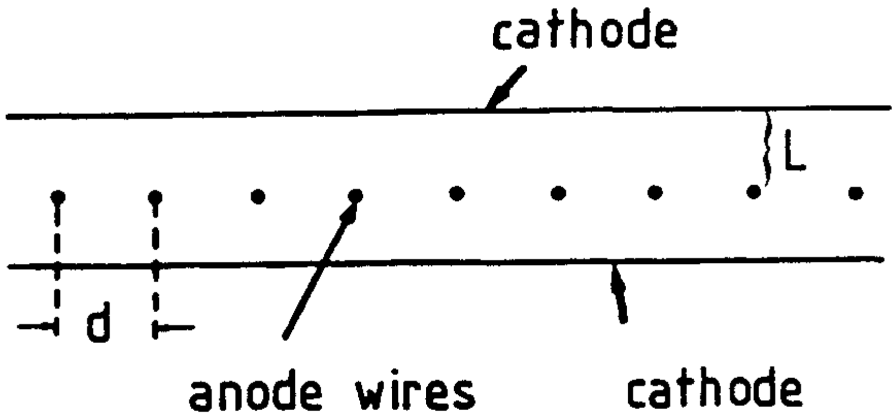
- To stop discharge:
  - Make charge resistor big enough so voltage drops enough (quenching by resistor)
  - Add alcohols (methylal, ethylaclohol) or hydrocarbons (methan, ethane, isobutane) to counting gas (usually argon):
    Absorb UV photons, reduce free path

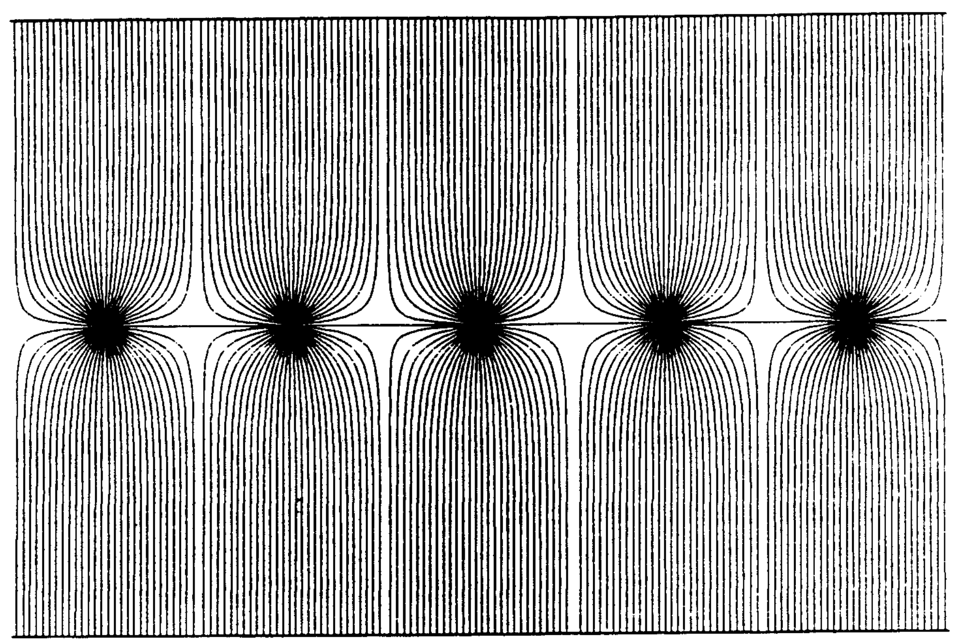
Summary Gas Multiplication



Multiwire Proportional Chambers

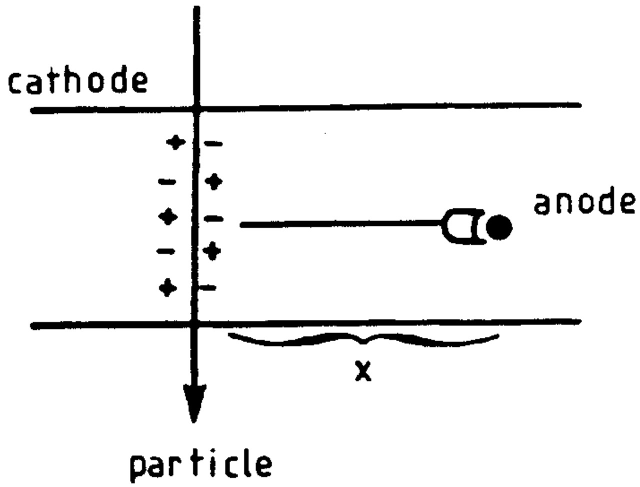
- George Charpak, beginning of 1960's, Nobel Price 1992
- Typical wire distance d: a few mm ($> 0.8\,\mathrm{mm}$)
- Typical wire diameter: $10\,\mu\mathrm{m} - 30\,\mu\mathrm{m}$
- Sizes: up to square meters. Limited by wire tension and electrostatic repulsion.
- Electronic: Discriminator (threshold).
- Resolution: $\sigma(x) = d/\sqrt{12}$
- space information only in one dimension
- Rotate second identical module for other dimension
- Segmented cathode readout for other dimension

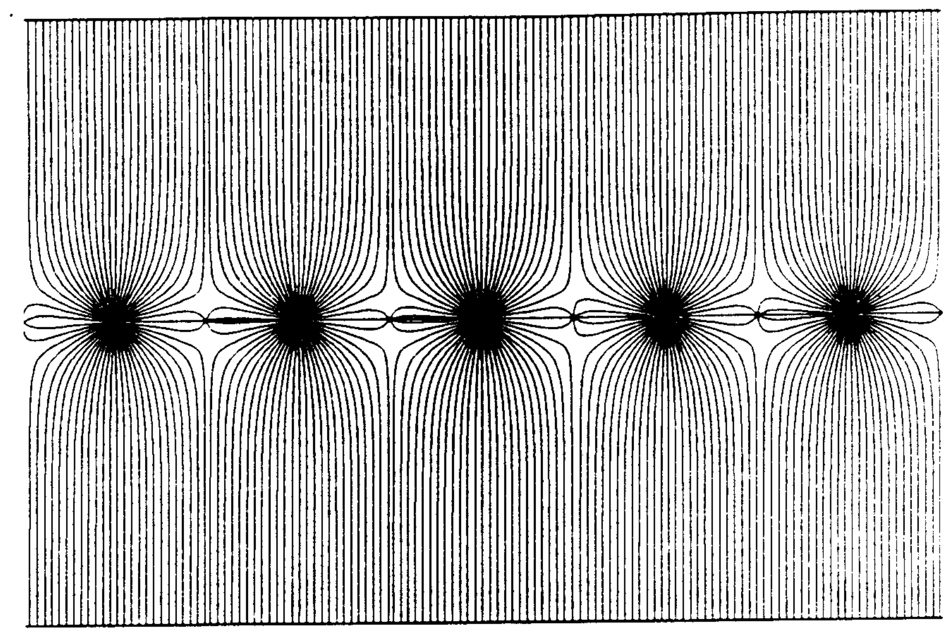





SENSOR HEAD
#6
SENSOR HEAD
#7

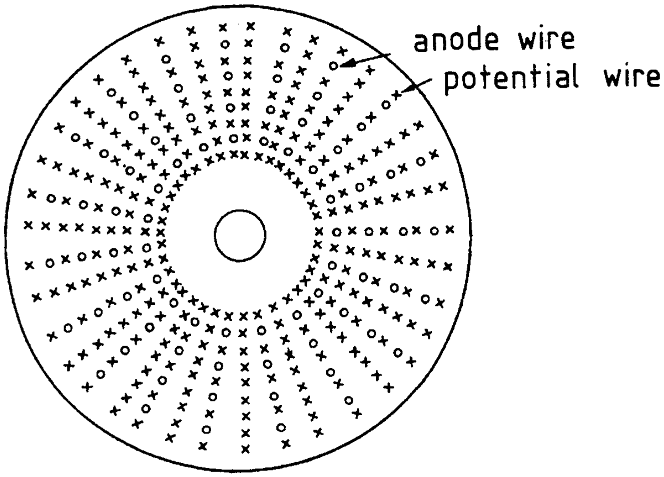
Planar Drift Chambers

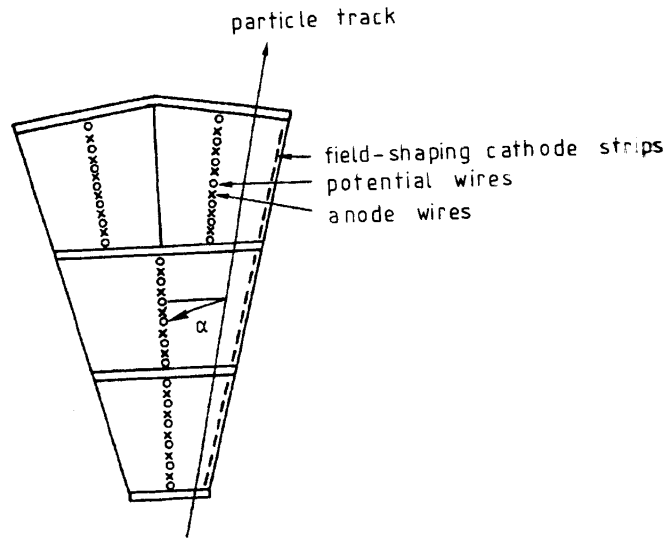


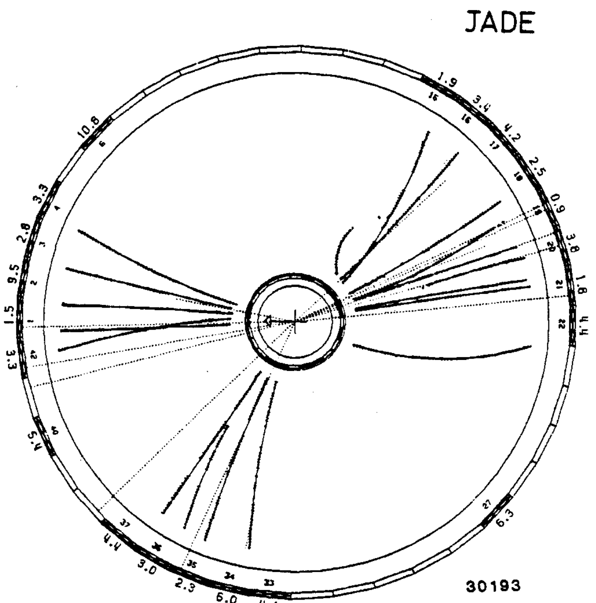


- Heintze, Walenta, ≈ 1968, also others.
- Make wires further apart
- use drift time to wire as additional information
- additional potential wire
- drift distances several cm
- resolution: limited by diffusion.
  small chambers: $\sigma > 20\,\mu$m
  larger chambers a few 100 μm

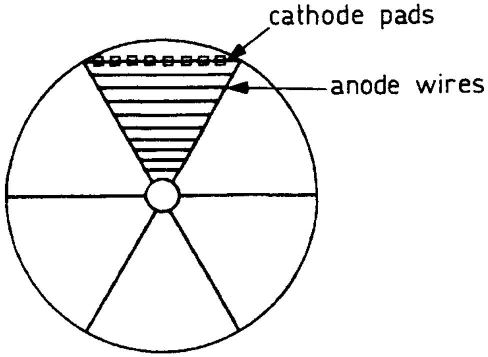
Cylindrical Drift Chambers / Jet Chambers

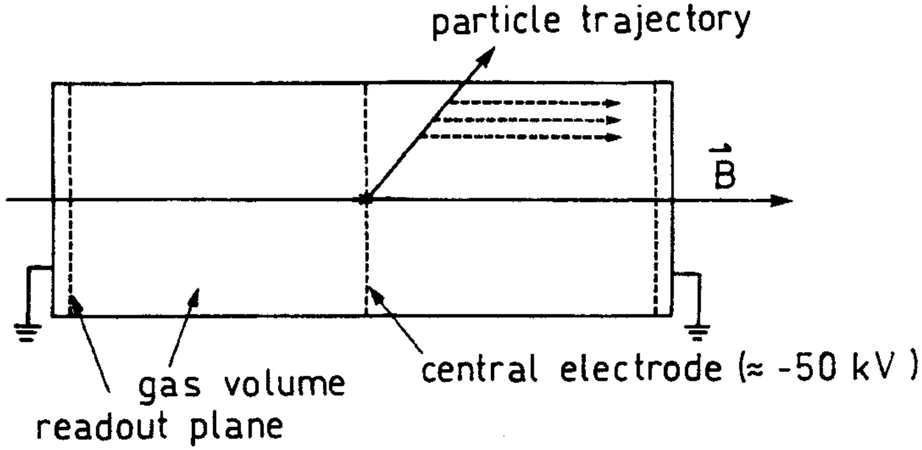


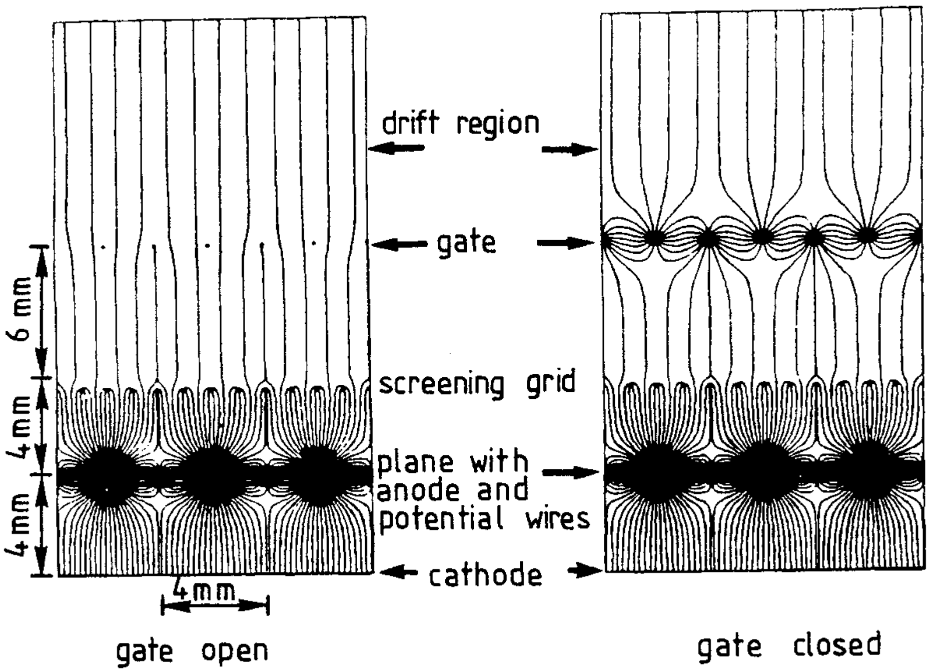




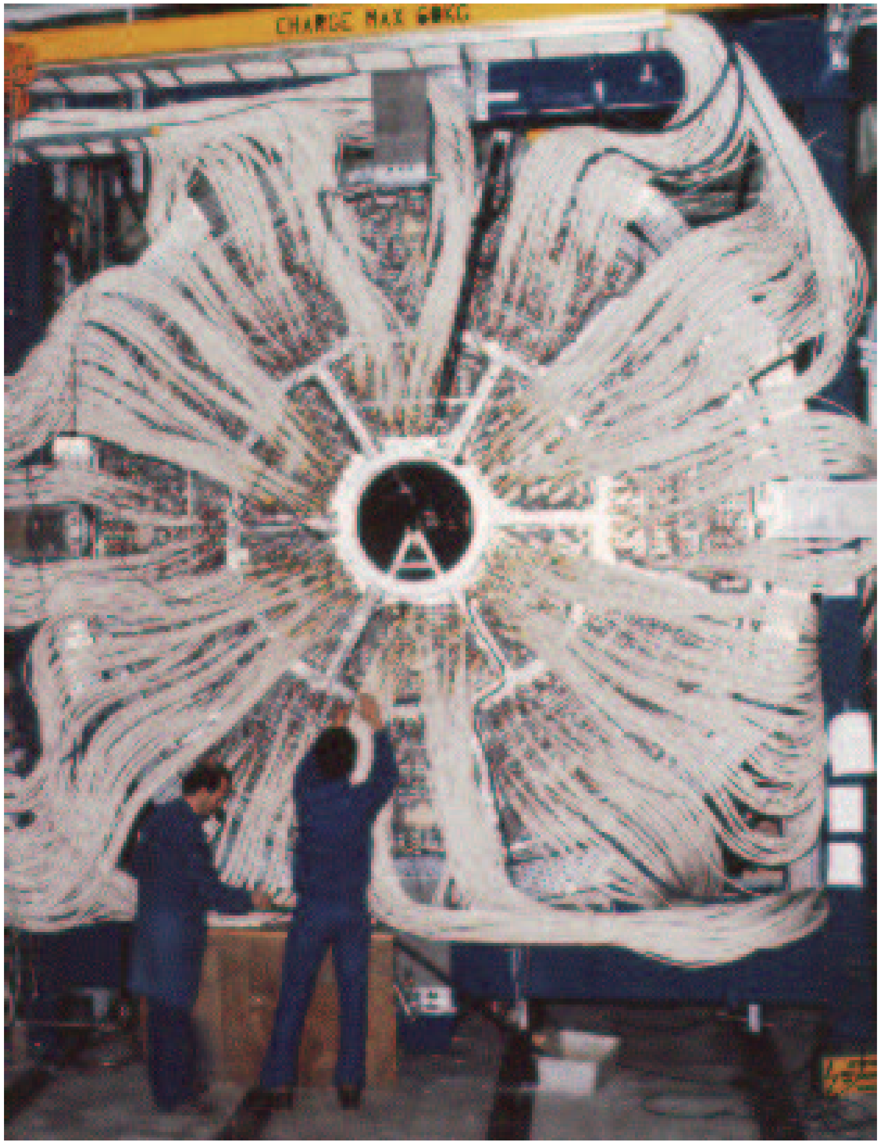
Time Projection Chamber



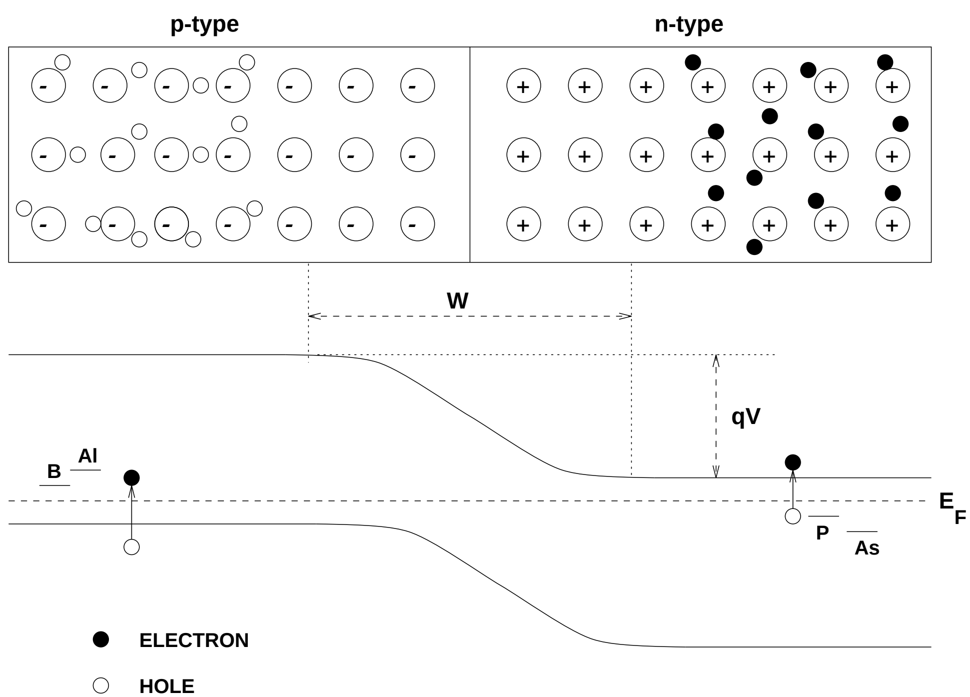


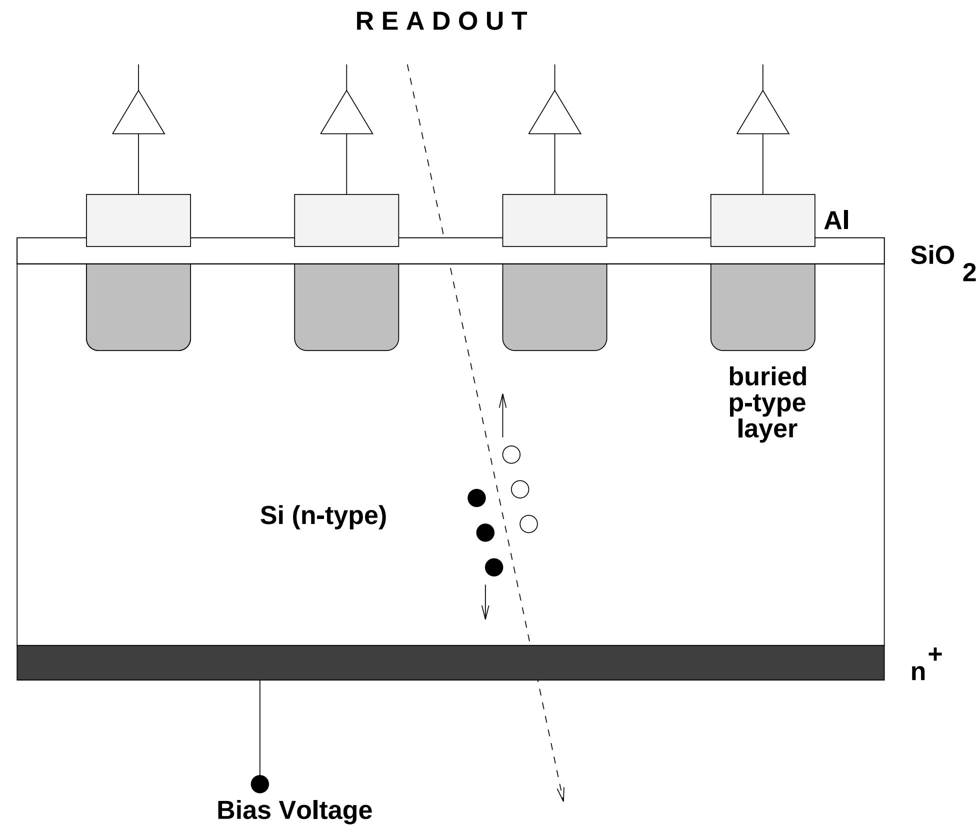


Aleph TPC



Solid State Tracking Detectors – Silicon





p-n junction (diode).

Silicon:

$dE/dx \approx 3.8\,\mathrm{MeV/cm}$, Band Gap $1.1\,\mathrm{eV}$

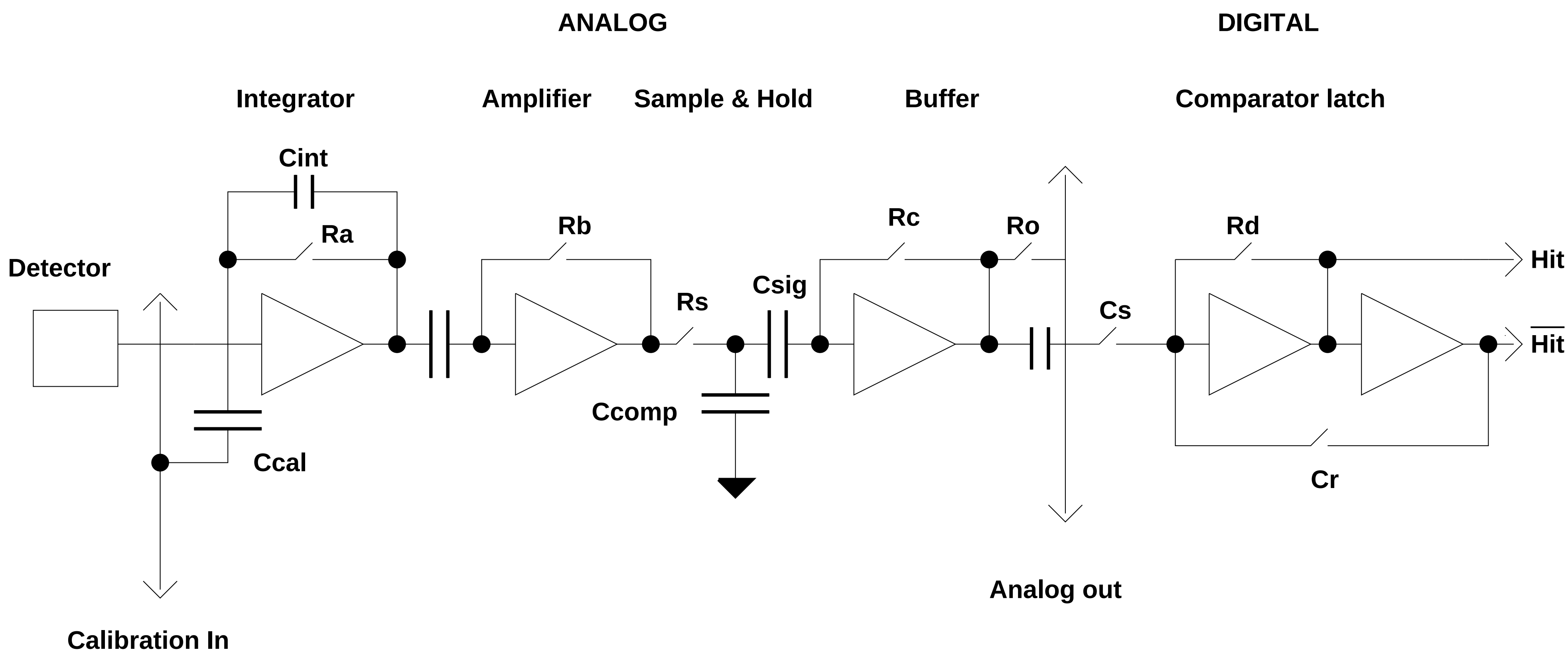
$3.6\,\mathrm{eV}$ to produce one electron-hole pair

Typical thickness: $300\,\mu\mathrm{m}$

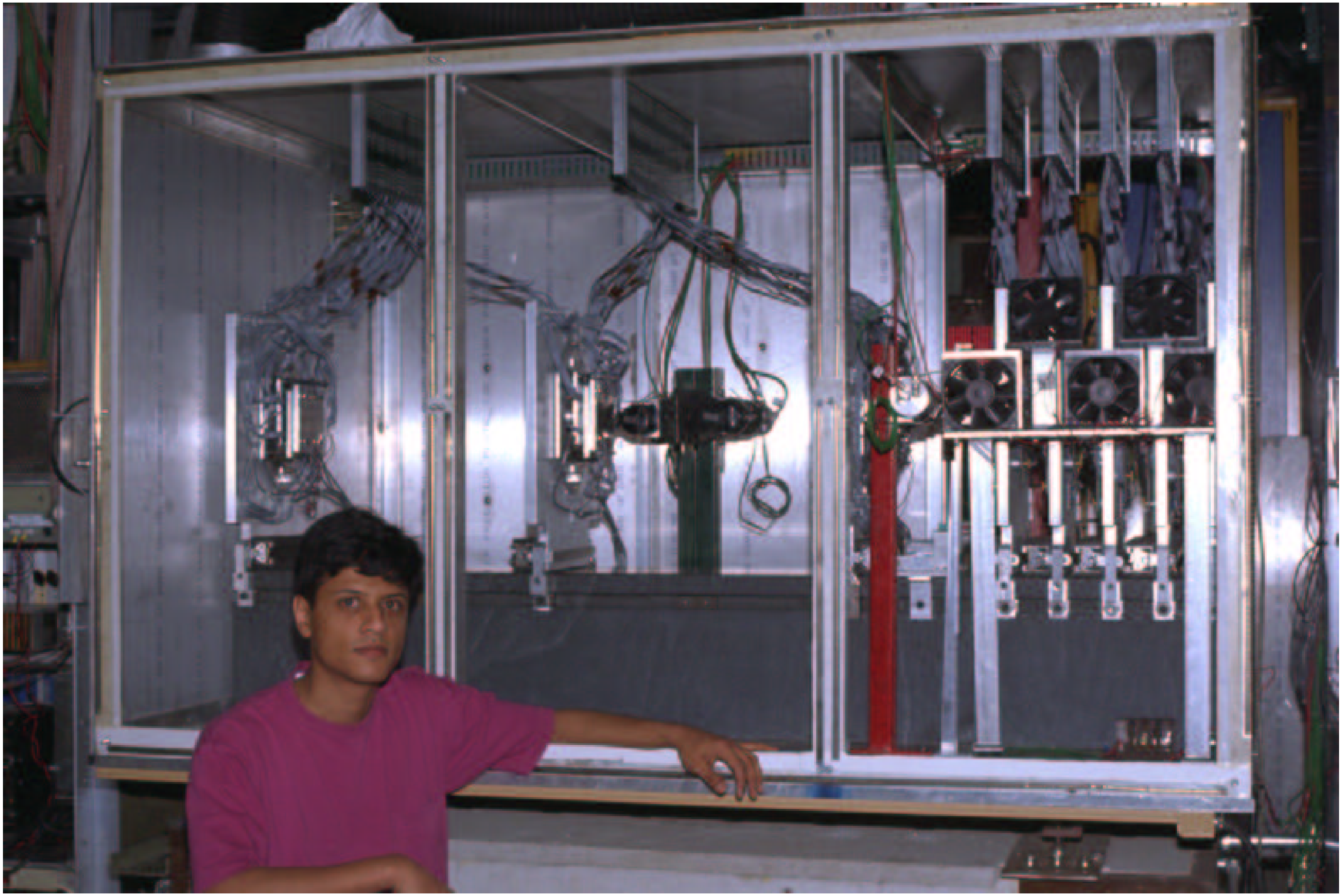
Strip Distance: $\geq 10\,\mu\mathrm{m}$

Silicon Strip Detectors (cont.)

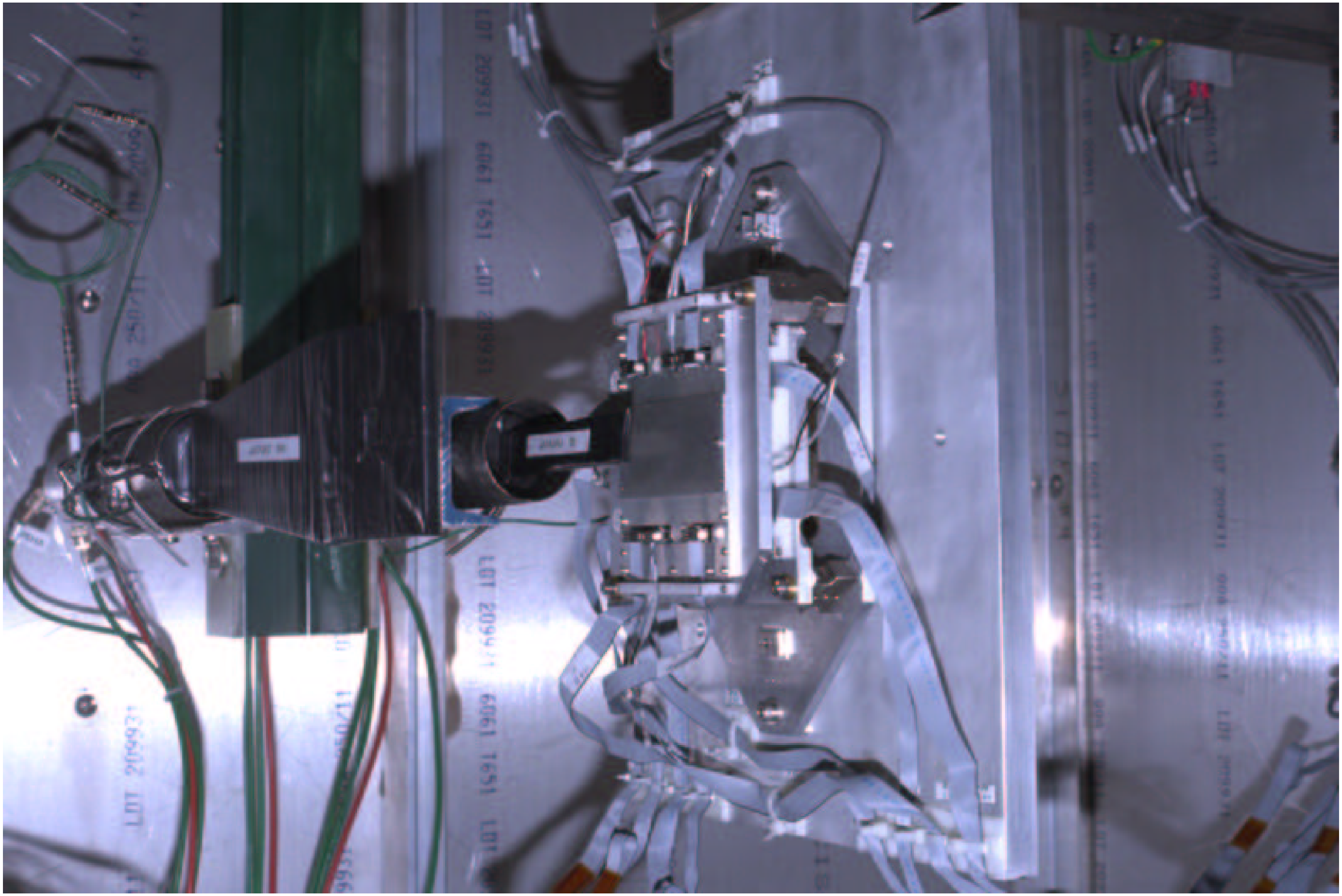
The real problem is the readout electronics. Need amplifiers etc every 10 μm!

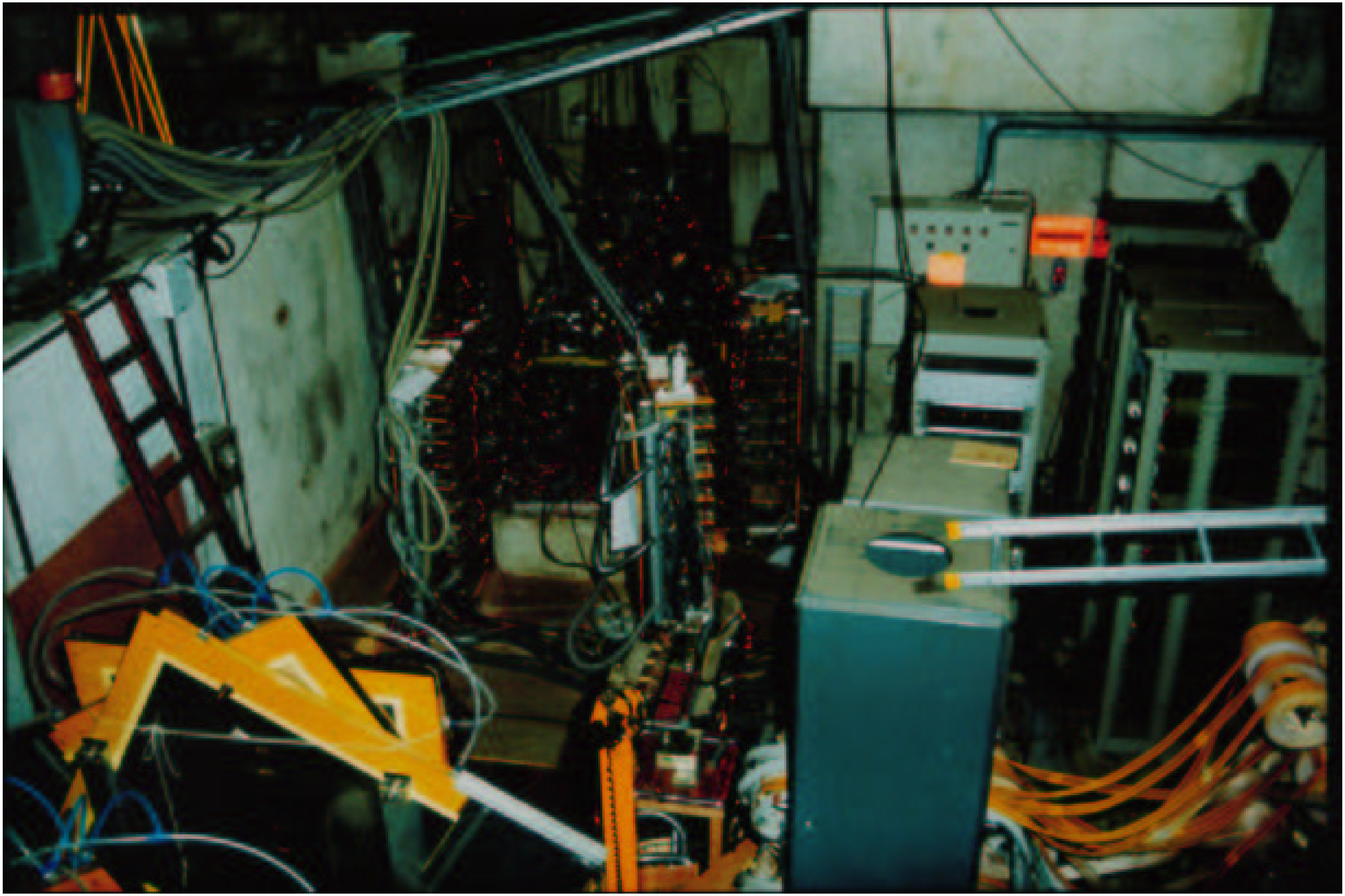


Example: SVX-I layout (for every strip!)

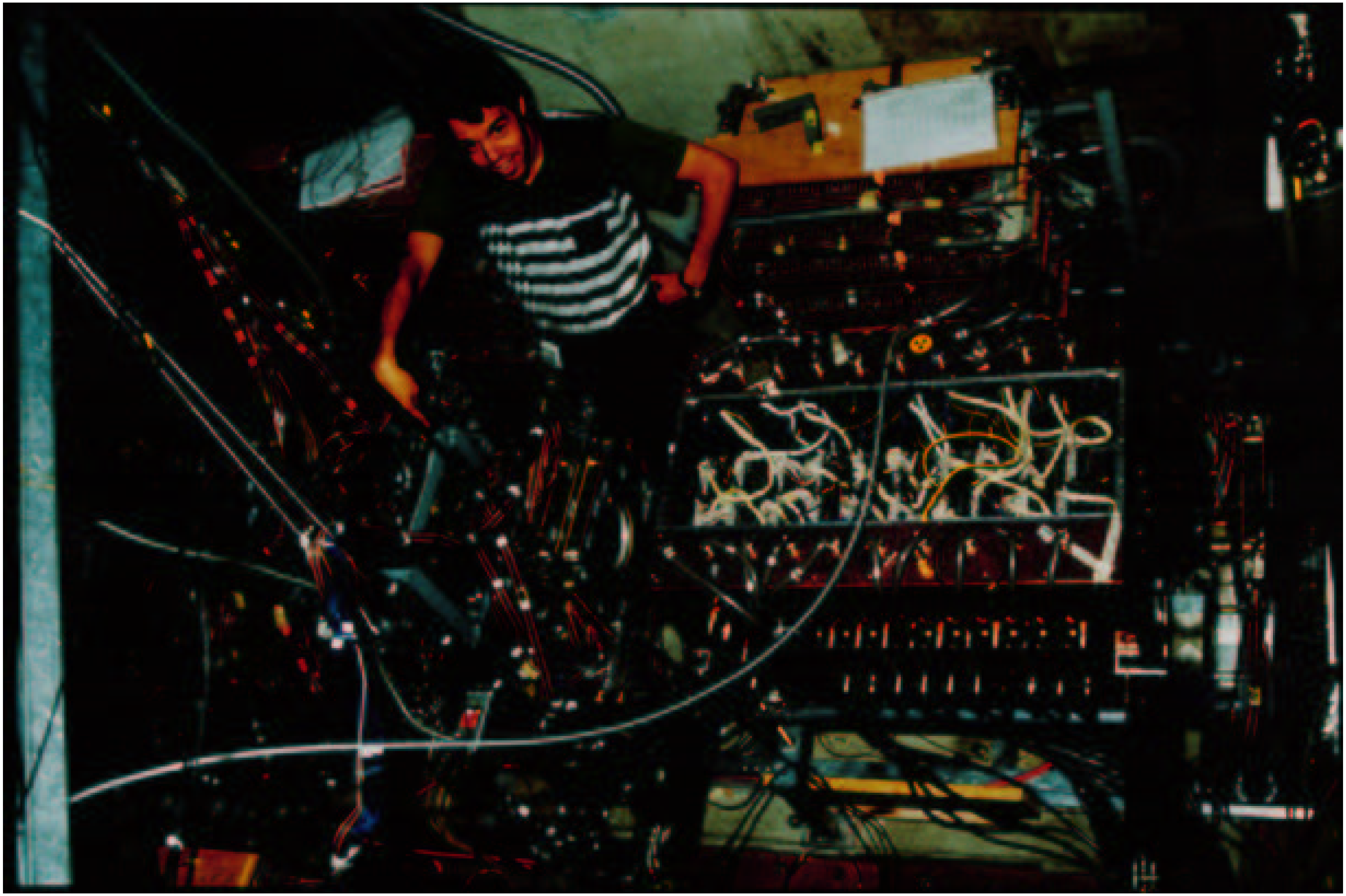


SELEX Target region (1996). 75000 strips





WA89 Target Region (1990)



WA89 Target Region (1990). Watch the cables!

New Vertex Detector for CDF (or D0?). 1 Million strips

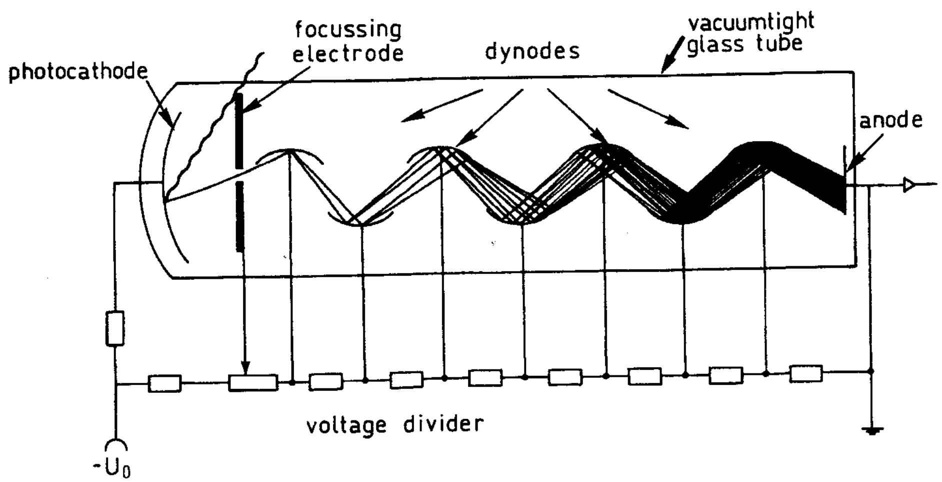
Other Silicon Detectors

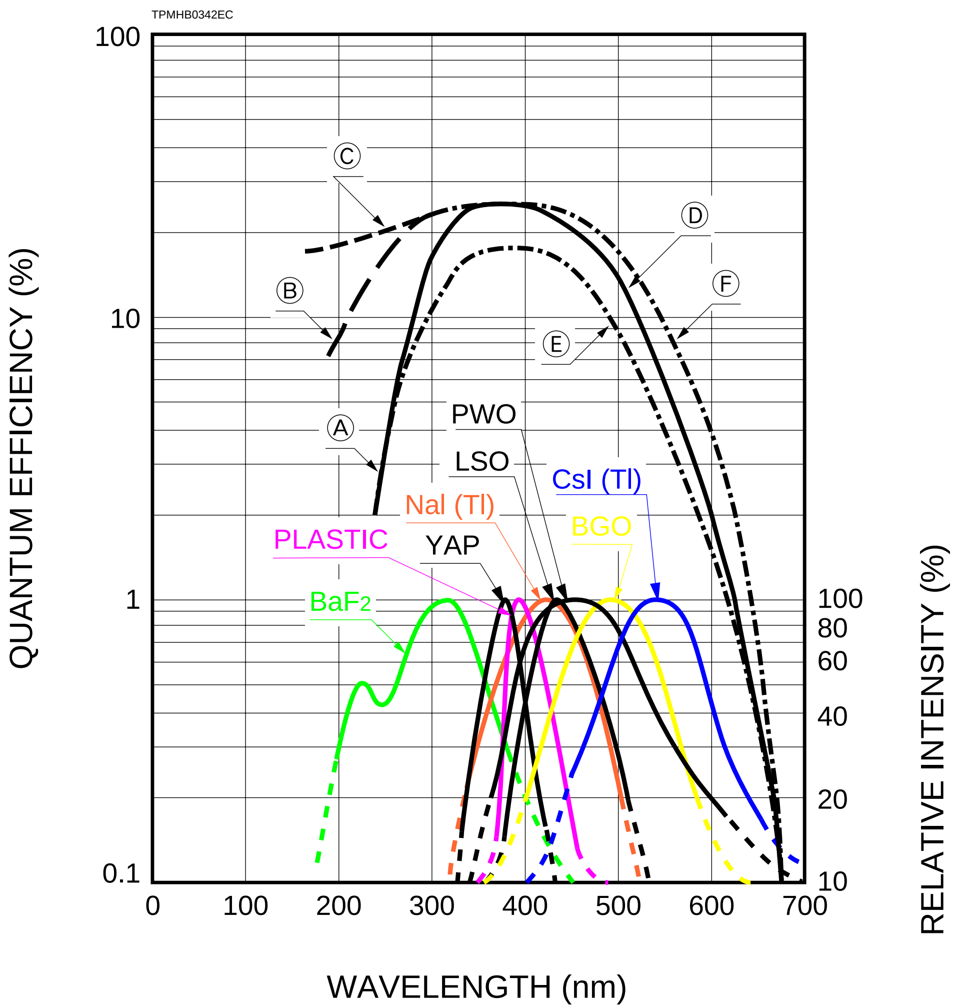
- Double Sided Strip Detectors
  - Has strip structure also on back side, under 90°
  - Still no real 3d information
  - used to minimize material (multiple scattering)
  - more difficult to operate (noise)

- Silicon Drift
  - Same idea as (wire) drift chamber: Use time information
  - drift over several cm achieved (example: ALICE prototype)

- Silicon Pixel Detectors
  - No strips, but (usually rectangular) pixels
  - bonding for electronics very complicated, but doable (example: BTeV prototype)
  - give real 3d information
  - Usable for trigger

Photomultipliers

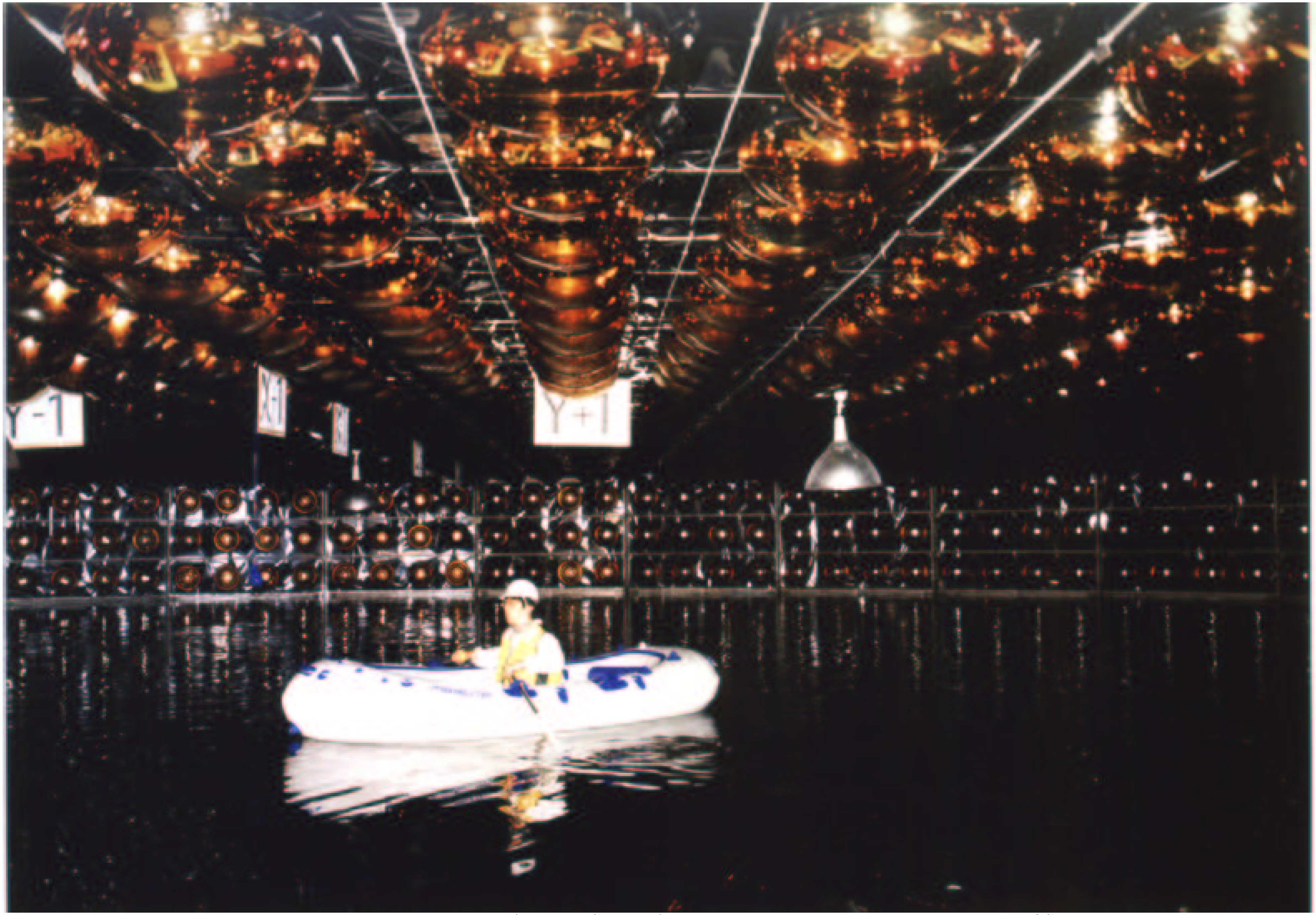




Conversion via photoelectric effect:
One photon to one electron, electrons multiplied
Typical efficiencies: up to 25%

Photomultipliers (cont.)

Available from 3/8 inch diameters to ≈ 40cm diameter.
Entrance windows on top ("head on") or on sides ("side on")


Y+1

Energy Measurement: Calorimeters

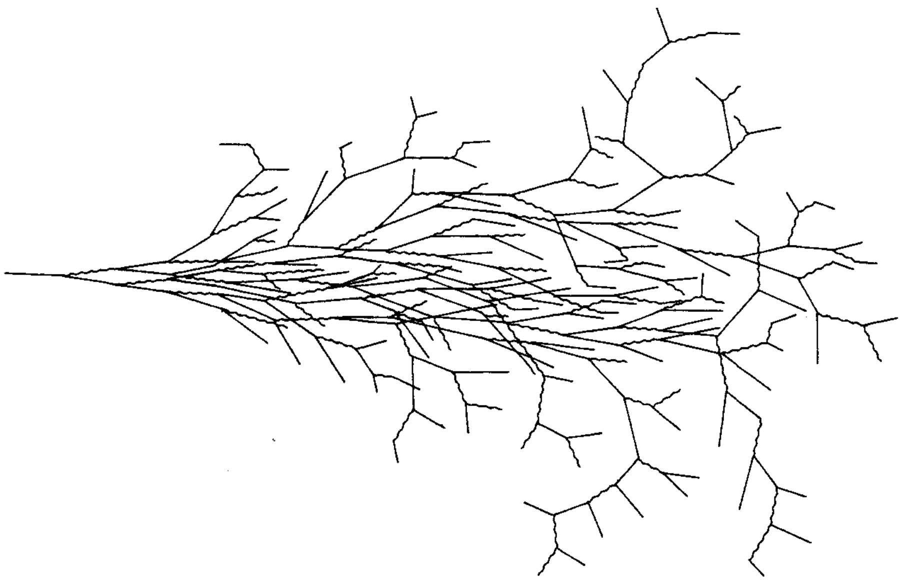
- Shower has to be absorbed totally. If not: reduced resolution due to fluctuations

- different optimization needed for electrons/photons and hadrons

- for electrons/photons: governed by Radiation Length X_0
- for hadrons: governed by Interaction Length λ_I

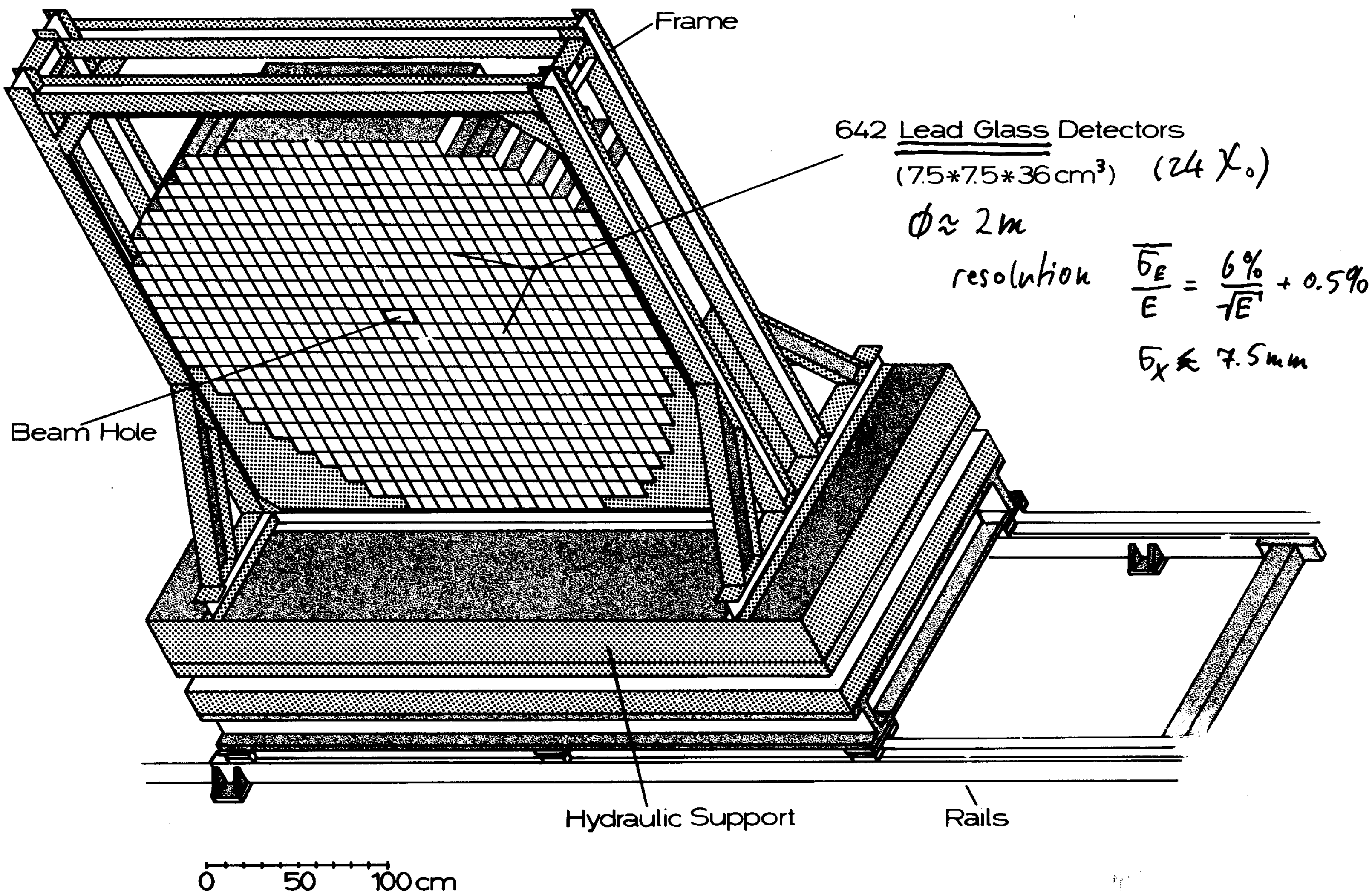
- for hadrons in addition: Need “compensation” due to electromagnetic part of shower.

Electromagnetic Calorimeters



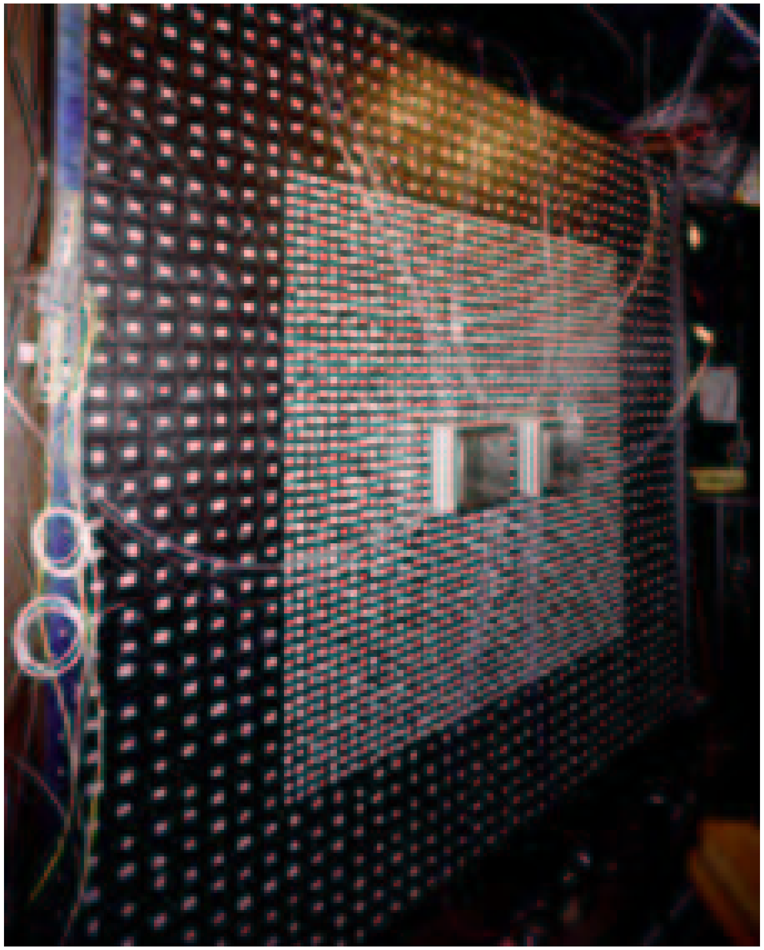
- Remember: relative Energy resolution is $\propto 1/\sqrt{E}$
- Two basic designs:
  - Homogeneous calorimeter
  - Sampling Calorimeter (discussed in hadron calorimeters)
- Use of Crystals (CsI) or lead-glass, liquids
- segmentation: about Moliere Radius R_M
- depth: Enough to contain shower.

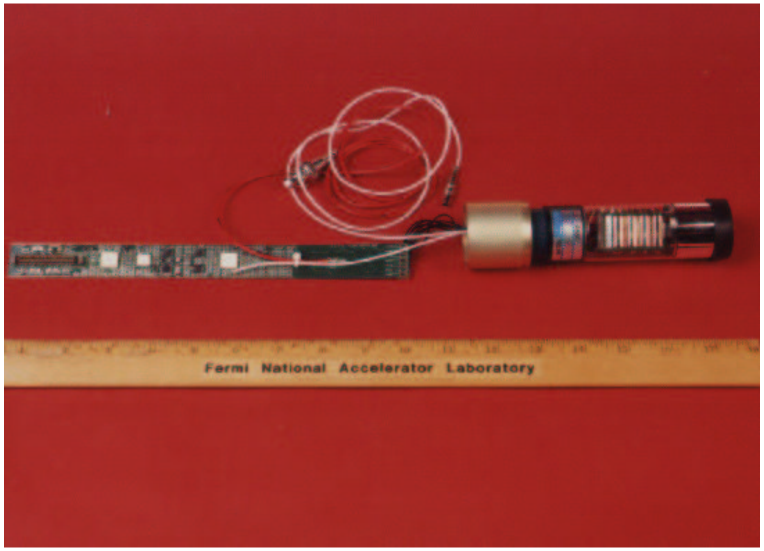
WA89 Lead-Glass Calorimeter



Lead-glass: Cherenkov light. Each block has one Photomultiplier attached.

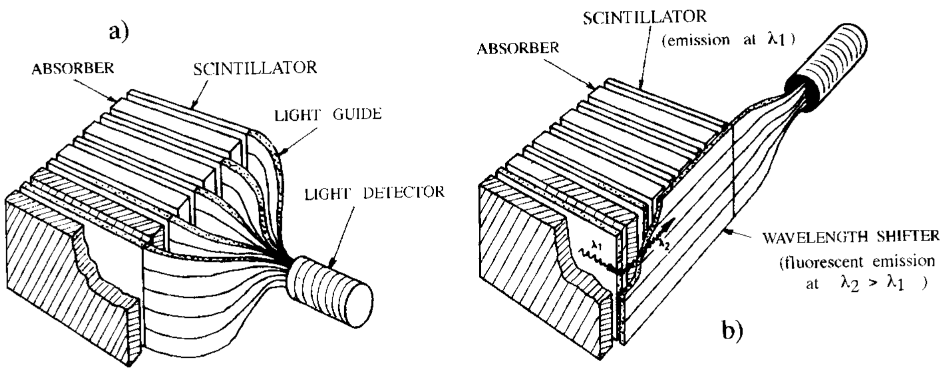
KTeV CsI Calorimeter





3100 CsI crystals

Sampling Calorimeters



- Something “heavy”, inactive:
  lead, uranium, iron (steel), ...
- Something “light”, active:
  plastic scintillator, wire chamber, liquid (ionization chamber), ...

- Problem: How to choose thicknesses?

- Problems to consider:
  1. Inactive part absorbs some of the produced shower particles, different for hadrons and electrons
  2. Some part of hadronic response is lost due to neutron absorption
  3. $\pi^0 \to \gamma\gamma$: All hadronic showers have electromagnetic component, responses (physics effects) are different.

Sampling Calorimeter Designs

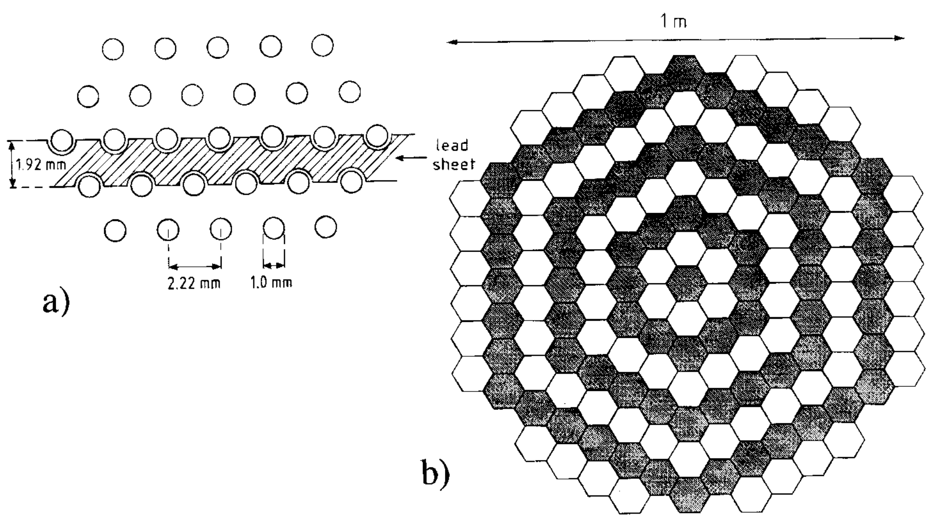
- Electromagnetic part was understood and good simulation software available (EGS)
- In the 1980's: First systematic studies for hadronic response

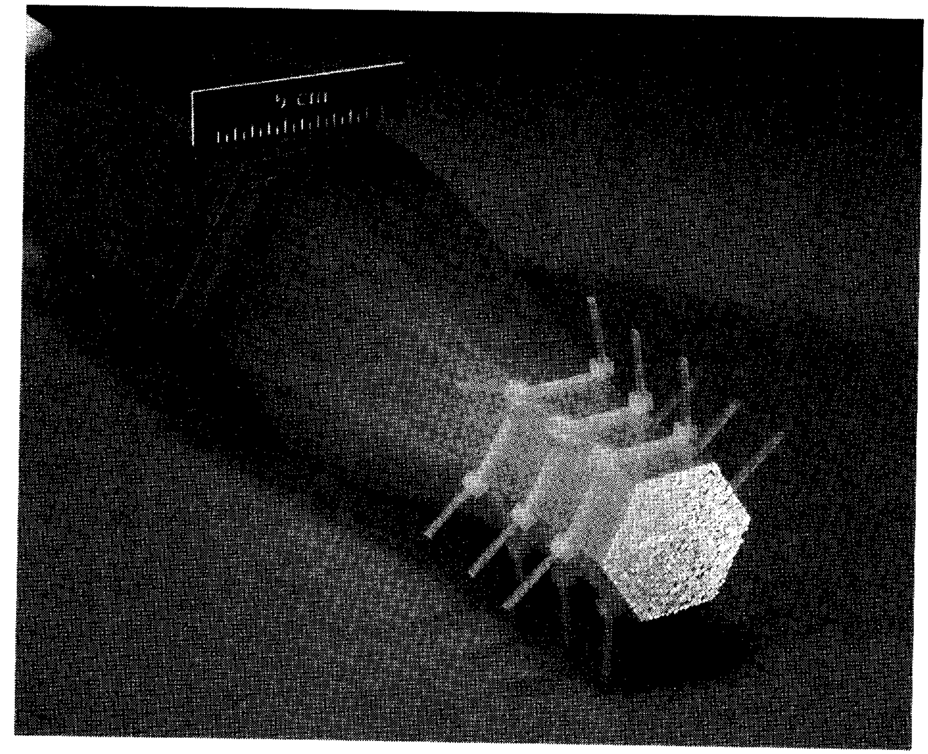
- First: Uranium / Scintillator. Very good resolution of first prototype.
- Idea was that fission gives back some of "lost" neutron energy.
- Later: By accident the first prototype was "compensated".

- mid-1980's: Systematic studies hadronic shower profiles, absorptions, by Wigmans et al.

- Result: One can tune **any** material combination to give identical responses to electrons and hadrons ("compensate"), due to different dependencies on Z of physics processes.
- Best resolution for hadrons only if calorimeter is compensated.
- Hadron resolution before: $\sigma_E/E \approx 100\,\%/\sqrt{E}$
- Best hadron resolution achieved (ZEUS, SPACAL): $30 - 35\,\%/\sqrt{E}$

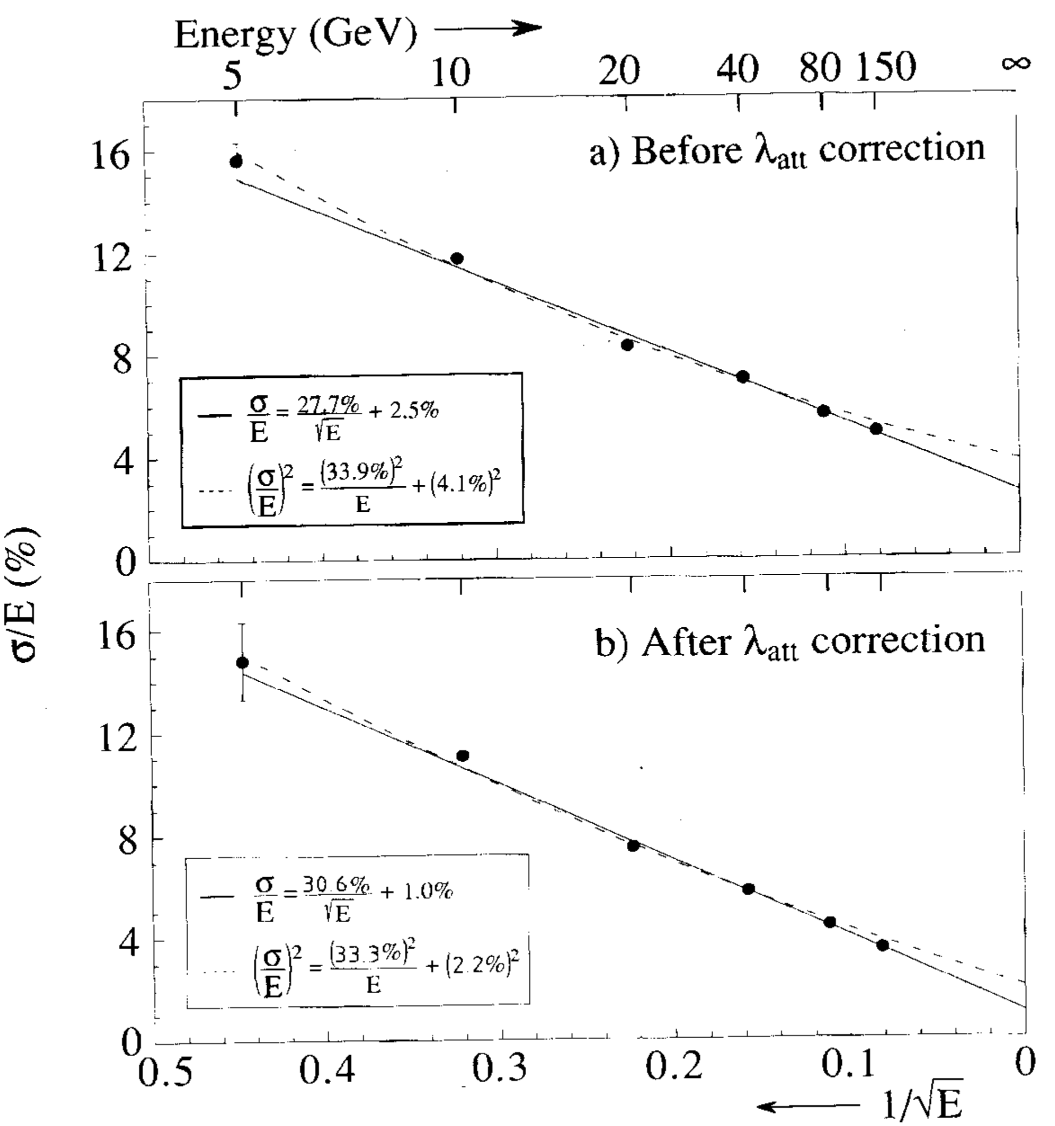
Spaghetti Calorimter (SPACAL)





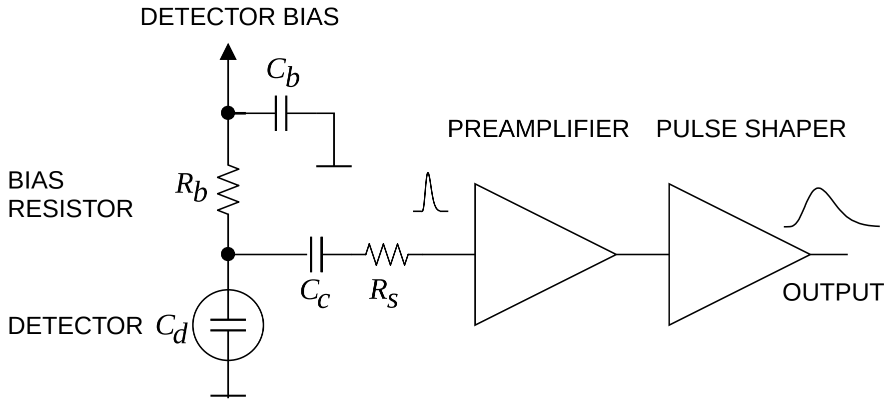
R.Wigmans, Colorimetry (Oxford Science, 2000)

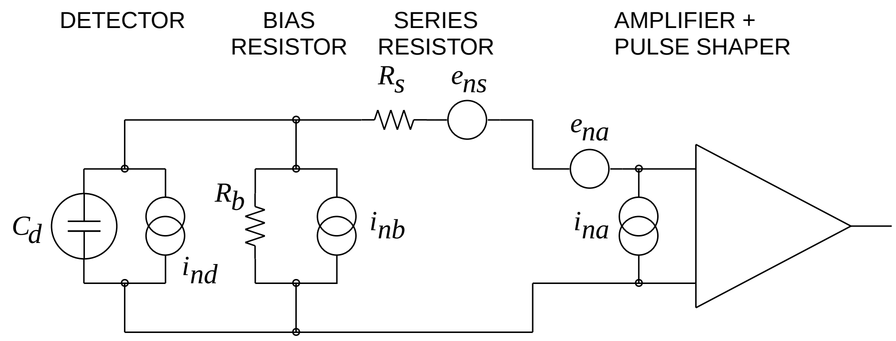
SPACAL Resolution



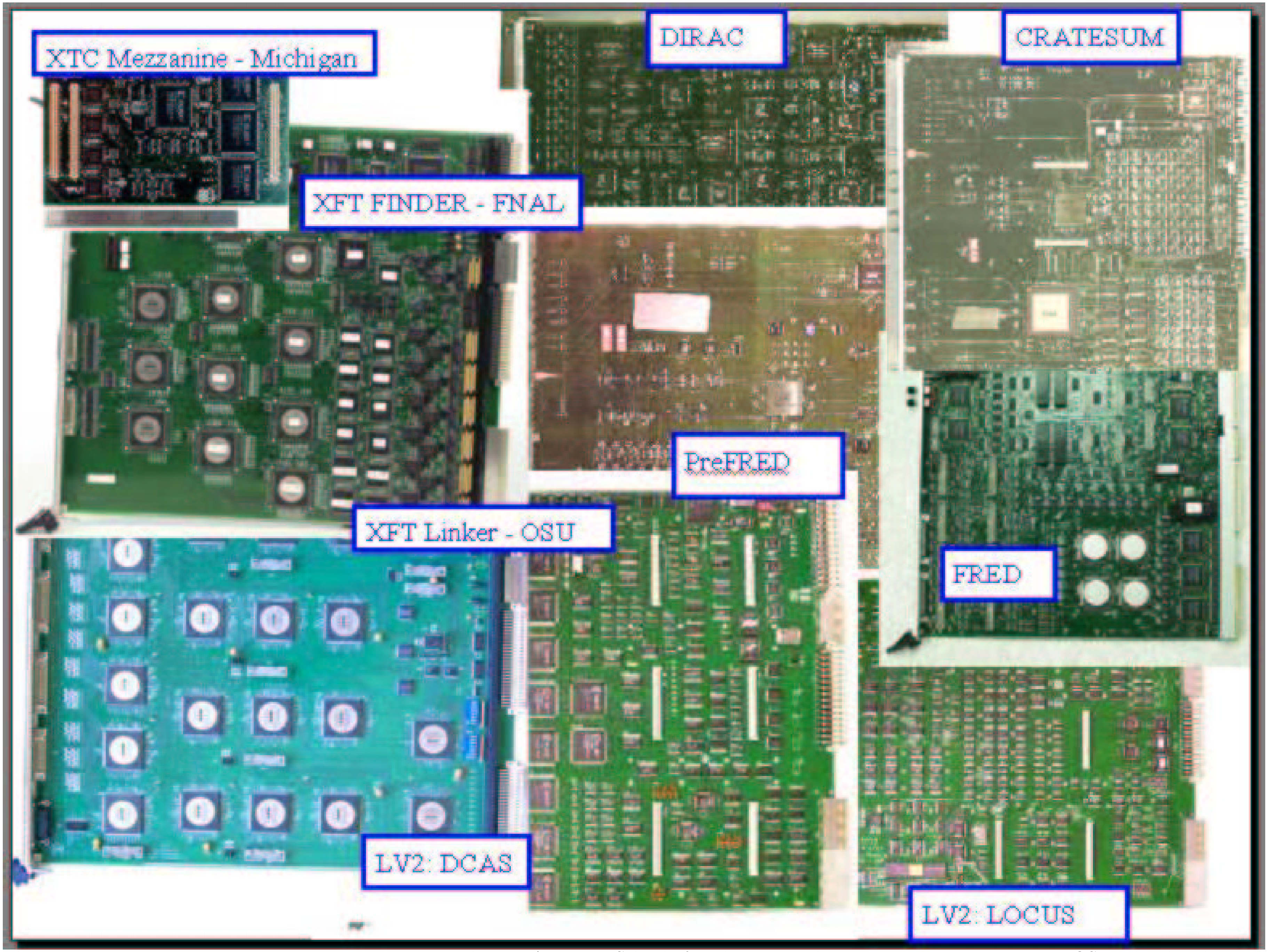
R.Wigmans, Colorimetry (Oxford Science, 2000)

Some words about Electronics





- Signals are fast $\Rightarrow$ High Frequency, high bandwidth
- Signals are small $\Rightarrow$ Noise is a problem
- Capacitance C_d is big, noise $\sim C^2$
- Need to analyse all noise contributions carefully (shot noise (leakage current), thermal noise, $1/f$ noise).
- Stray capacitances, stray inductances (printed circuits) are significant at high frequencies (≥ 100 MHz)
- Board layouts a sensitive to signal speed (~ 5 cm/nsec)


XTC Mezzanine - Michigan
DIRAC
CRATESUM
XFT FINDER - FNAL
PreFRED
XFT Linker - OSU
FRED
LV2: DCAS
LV2: LOCUS

Some words about Simulation

- Detectors are complex, complicated to build, expensive
- Within one sub-detector and different sub-detectors interferences (mostly destructive) possible
- LONG before building even prototypes simulation of part or full behavior and responses of sub-detectors or full detectors necessary
- GEANT is the usual tool for simulations. Manual has 700 pages.
- GEANT is slow. Often necessary to parametrize detector response

Summary of Second Part: Basic design of detectors

- Gaseous detectors (wire chambers)
- Silicon Microstrips
- Calorimeters
- Electronics (connection Trigger and DAQ lecture)
- Simulation

Part 3: Particle Identification

- Identification of neutral particles
- Identification of charged particles

Neutral particles

- Measure total energy (Calorimeter)
- If no charged track points to signal in Calorimeter: It's a neutral
- Usually not too many possibilities left.
  Example: Hadron calorimeter, no track: most likely a neutron (or K_L^0)
- Electromagnetic calorimeter, track, signal: Measure "E/p".
  $E/p = 1$ for electrons, $E/p < 1$ for pions

- Long-lived neutral particles (Hyperons), short lived particles (charm, beauty):
  Measure 4-vector of decay products and calculate invariant mass.

Identification of Charged Particles

What is Particle Identification?

Two major applications:

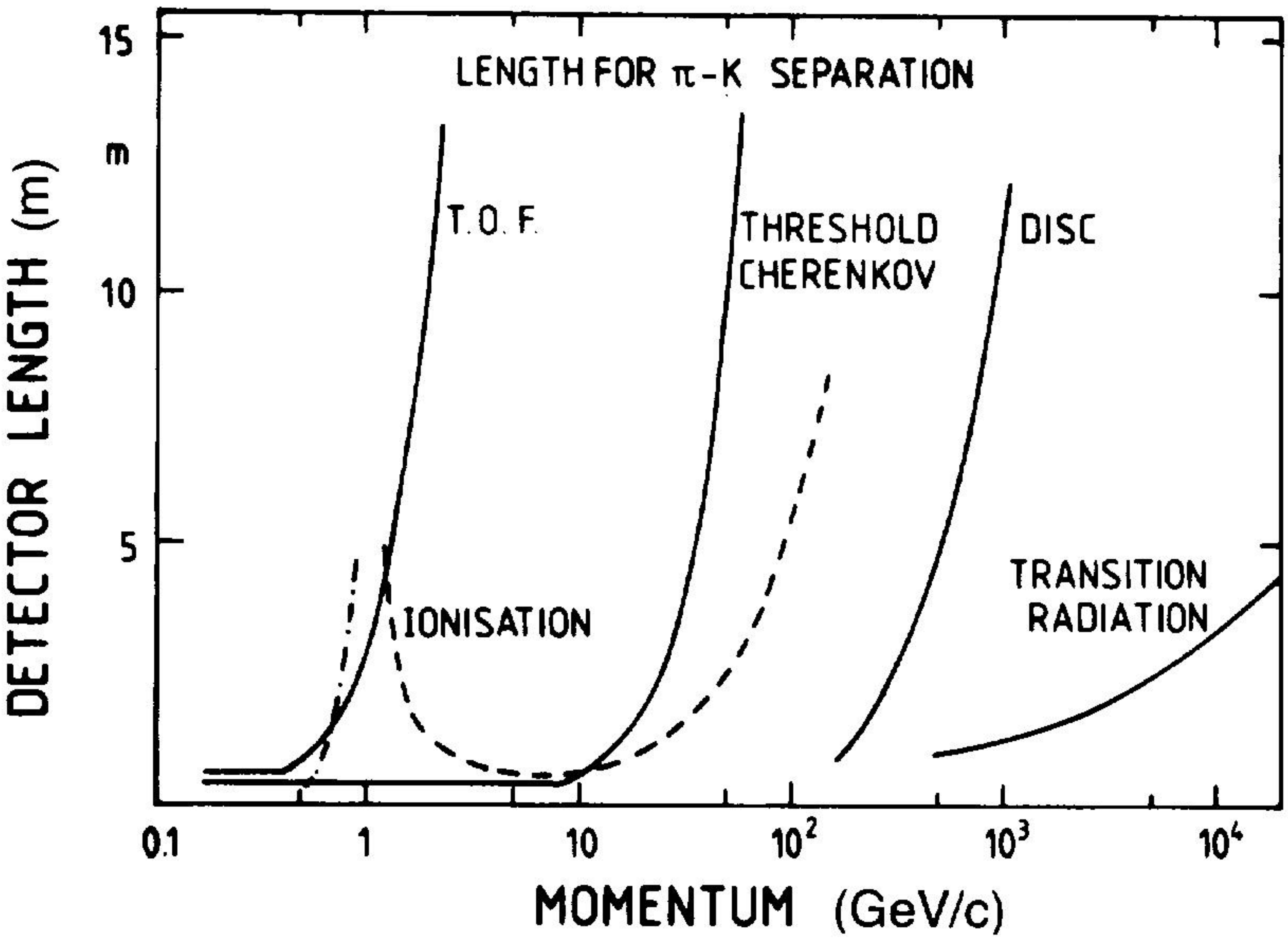
1. Beam Particle Identification (Fixed Target)
2. Identification of decay products

In both cases the momentum of the particle is known:

1. By beamline elements (only small momentum bin)
2. Measured by a magnetic spectrometer (wire chambers)

$\Longrightarrow$ Particle Identification reduces to measure the total Energy (calorimeter) or using some velocity-dependent effect (Time of flight, dE/dx, Cherenkov, Transition radiation)

Fig. 5.30. Length of detectors needed for separation of π and K mesons.



First some Physics Example...

Reconstruction of Λ_c^+

- Λ_c^+ baryon consists of (udc) quarks
- Mass $m_0 = 2.284.9\,\mathrm{GeV}/c^2$ (remember: proton $0.938\,\mathrm{GeV}/c^2$)
- Lifetime: $\tau = 2.0 \cdot 10^{-13}\,\mathrm{sec}$
- Decays to $\Lambda_c \rightarrow pK^-\pi^+$ in $5.0\,\%$ of the time.
- Only in 1 out of 1000 collisions a charm quark gets produced.

Special Theory of Relativity:

$$
\begin{aligned}
E &= m \cdot c^2 \\
m &= m_0 \cdot \gamma \\
\gamma &= \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{E \cdot c^2}{m_0} \\
p &= m \cdot v \approx m_0 \cdot \gamma \cdot c \\
\text{Time dilation:} \quad t &= t_0 \cdot \gamma \\
\text{Mean flight path:} \quad L &= c \cdot \tau \cdot \gamma
\end{aligned}
$$

$\Longrightarrow$ A Λ_c^+ with momentum $200\,\mathrm{GeV}/c$ flies on average $5.4\,\mathrm{mm}$

$\Longrightarrow$ Do a Fixed Target Experiment – But even there we cannot observe a Λ_c directly

What do we do?

- Measure type, direction, momentum, (the 4-vector) and charge of all decay products
- Apply momentum and energy conservation to "interesting" decay vertex and calculate energy and momentum of hypothetical mother particle
- Transform into rest system of mother particle to obtain rest mass
- Do this for a lot of events, fill histogram with results

Measuring direction and decay vertex

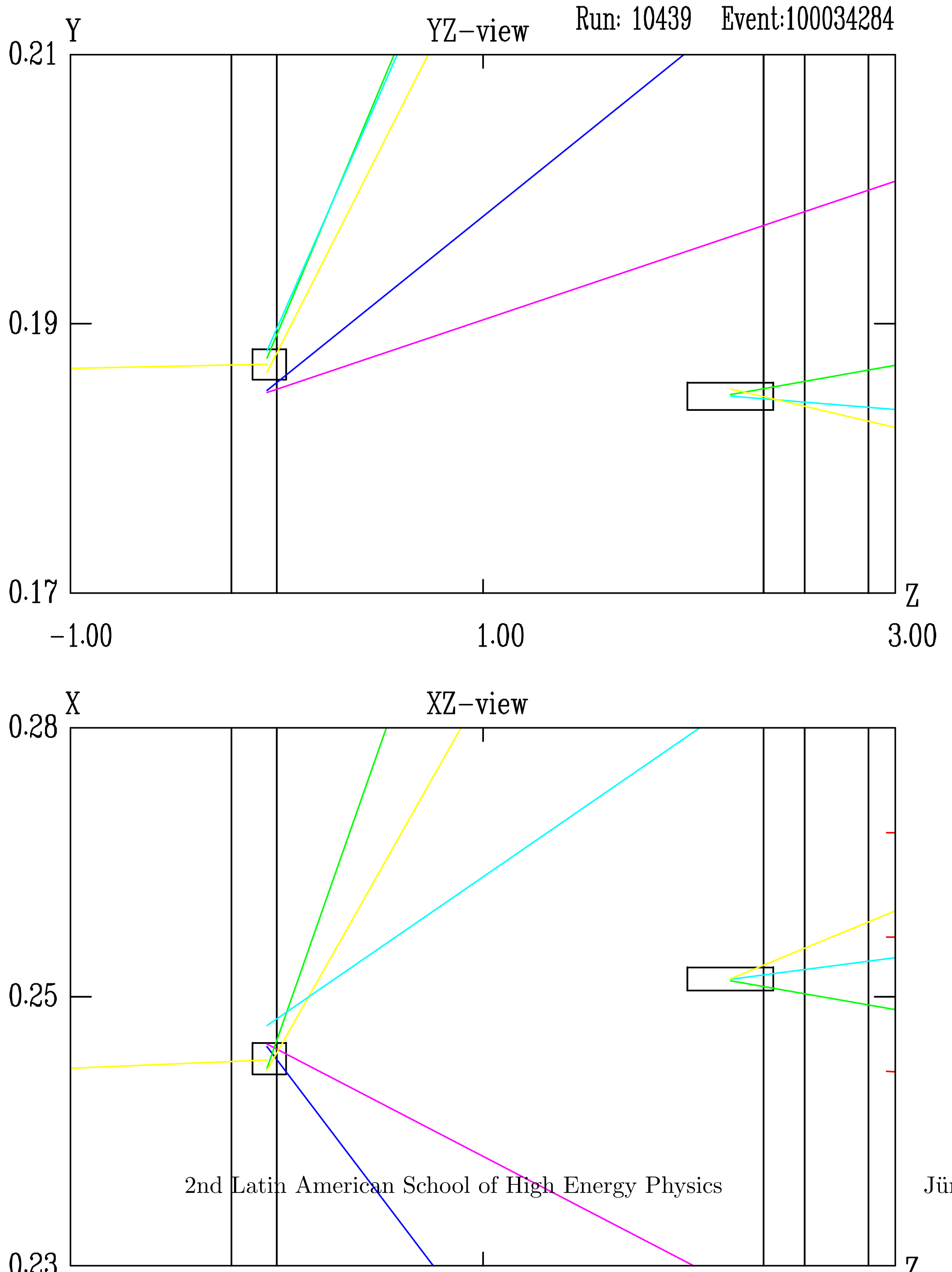
- Use silicon microstrip detectors

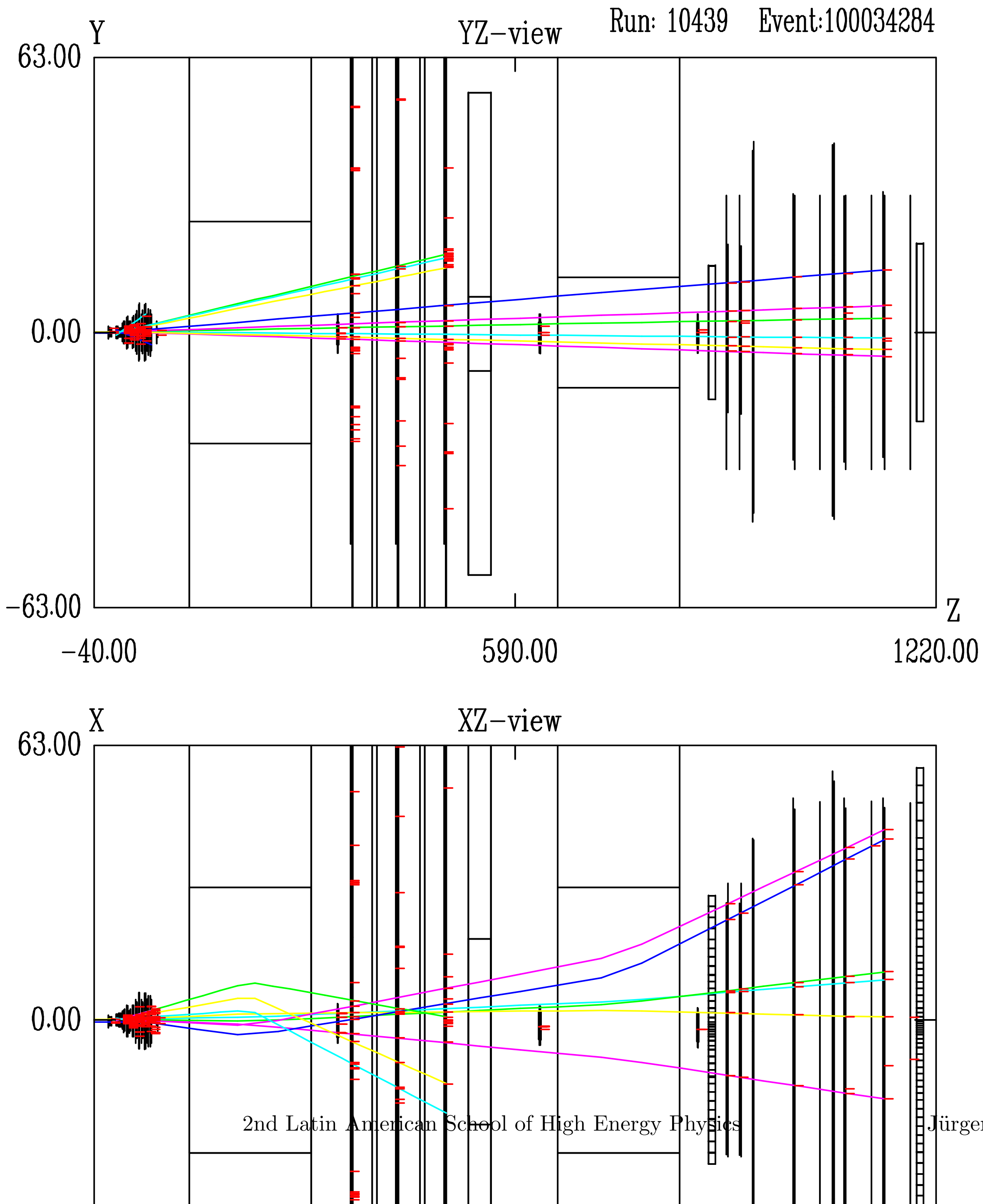
Measuring momentum and charge

- Deflection in magnetic field, measure track angles before and after with wire chambers

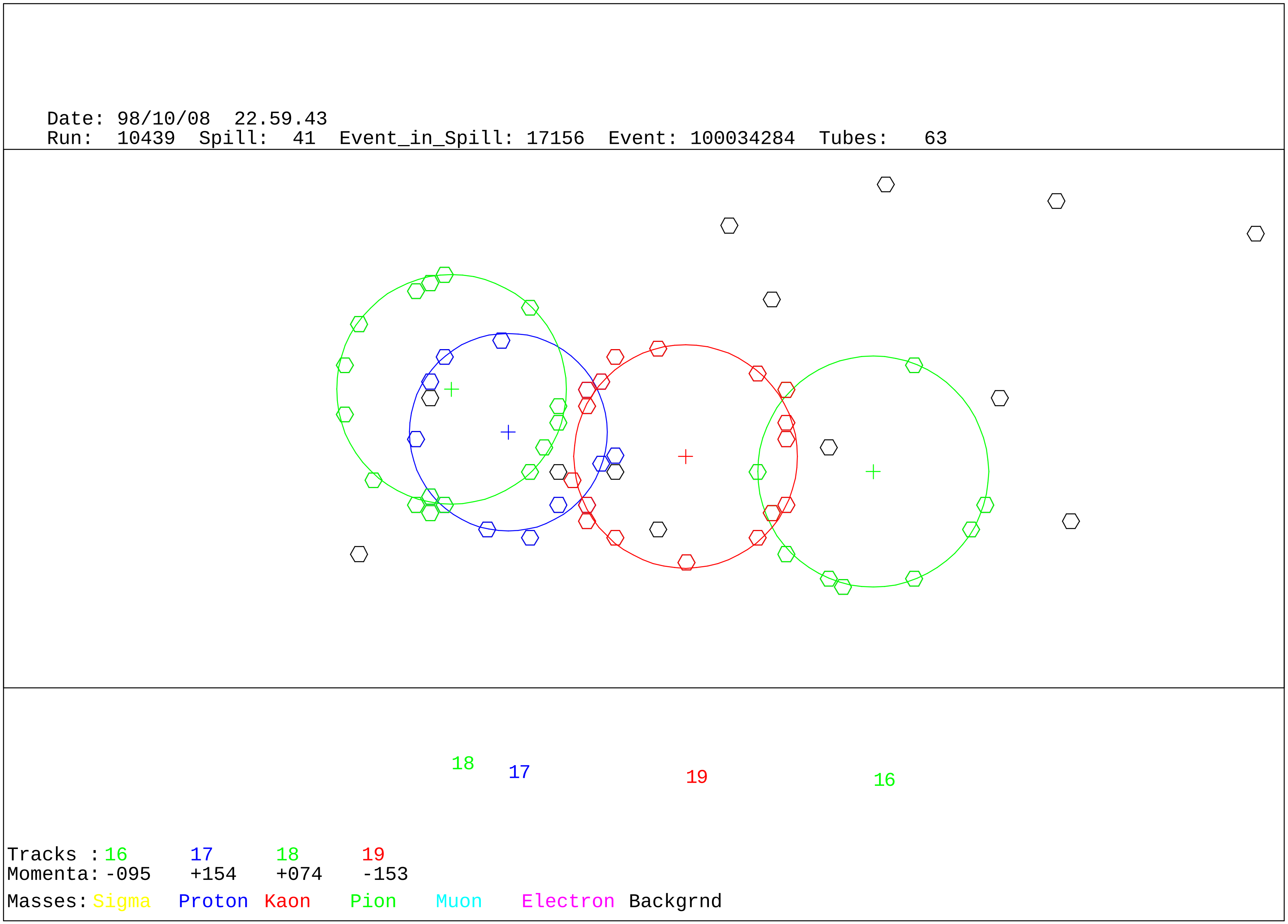
Measuring type (is it a proton?)

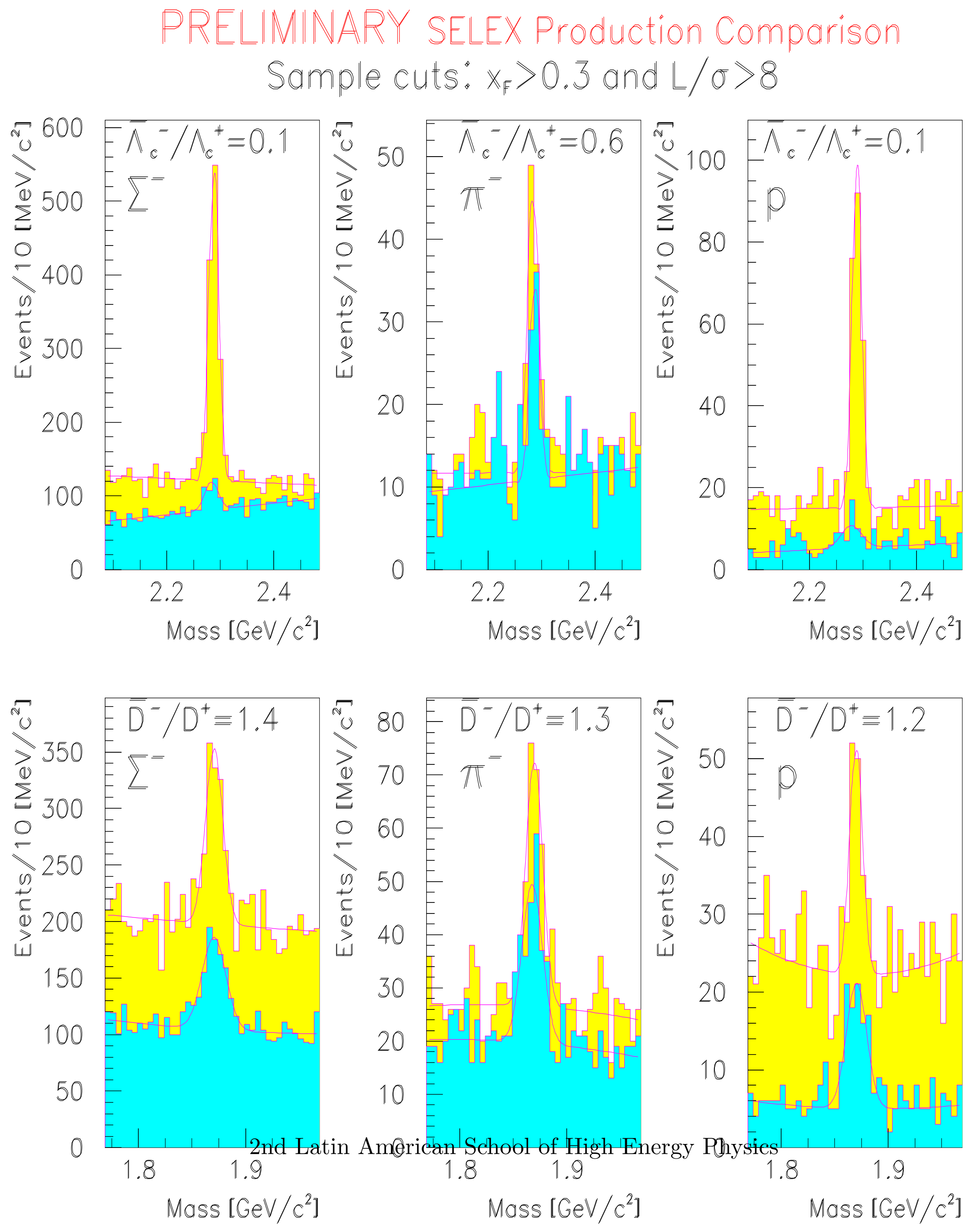
- Measure total energy in calorimeter, calculate mass
- Measure velocity with Cherenkov effect


Run: 10439 Event:100034284
YZ−view
Y
0.21
0.19
0.17
Z
−1.00
1.00
3.00
XZ−view
X
0.28
0.25
0.23
Z



Run: 10439 Event:100034284
Y
YZ-view
63.00
0.00
-63.00
-40.00
590.00
1220.00
Z
X
XZ-view
63.00
0.00


Date: 98/10/08 22.59.43
Run: 10439 Spill: 41 Event_in_Spill: 17156 Event: 100034284 Tubes: 63
18
17
19
16
Tracks : 16 17 18 19
Momenta: -095 +154 +074 -153
Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd


PRELIMINARY SELEX Production Comparison
Sample cuts: $x_F>0.3$ and $L/\sigma>8$
$\bar{\Lambda}_c^-/\Lambda_c^+=0.1$
Σ^-
$\bar{\Lambda}_c^-/\Lambda_c^+=0.6$
π^-
$\bar{\Lambda}_c^-/\Lambda_c^+=0.1$
p
$\bar{D}^-/D^+=1.4$
Σ^-
$\bar{D}^-/D^+=1.3$
π^-
$\bar{D}^-/D^+=1.2$
p
Events/10 [MeV/c^2]
Mass [GeV/c^2]

“Simple” Method of Particle Identification
Time–of–flight (TOF)

- Put two Scintillation Counters at a known distance
- Measure time difference between the two signals

Good time resolution: 150 psec.
Maximum distance: $\approx 10\,\mathrm{m}$ (detector), $\approx 100\,\mathrm{m}$ (beamline).
$\Longrightarrow$ Can measure difference between Kaons and Pions up to a few GeV/c
Also has problem at higher rate and/or multiple particles hitting the same scintillator

Radiation by Charged Particles

Radiation is emitted by a charge particle if:

1. $v > c/n$: Cherenkov radiation
2. $\vec{v}/c_{\text{ph}} = \vec{v} \cdot n/c$ changes
   (a) $|\vec{v}|$ changes: Bremsstrahlung
   (b) direction of $\vec{v}$ changes: Synchrotron radiation
   (c) n changes: Transition Radiation

Transition Radiation Detectors (TRD)

Transition Radiation: Reformation of particle field while traveling from medium with $\epsilon = \epsilon_1$ to medium with $\epsilon = \epsilon_2$.

Energy of radiation emitted at a single interface

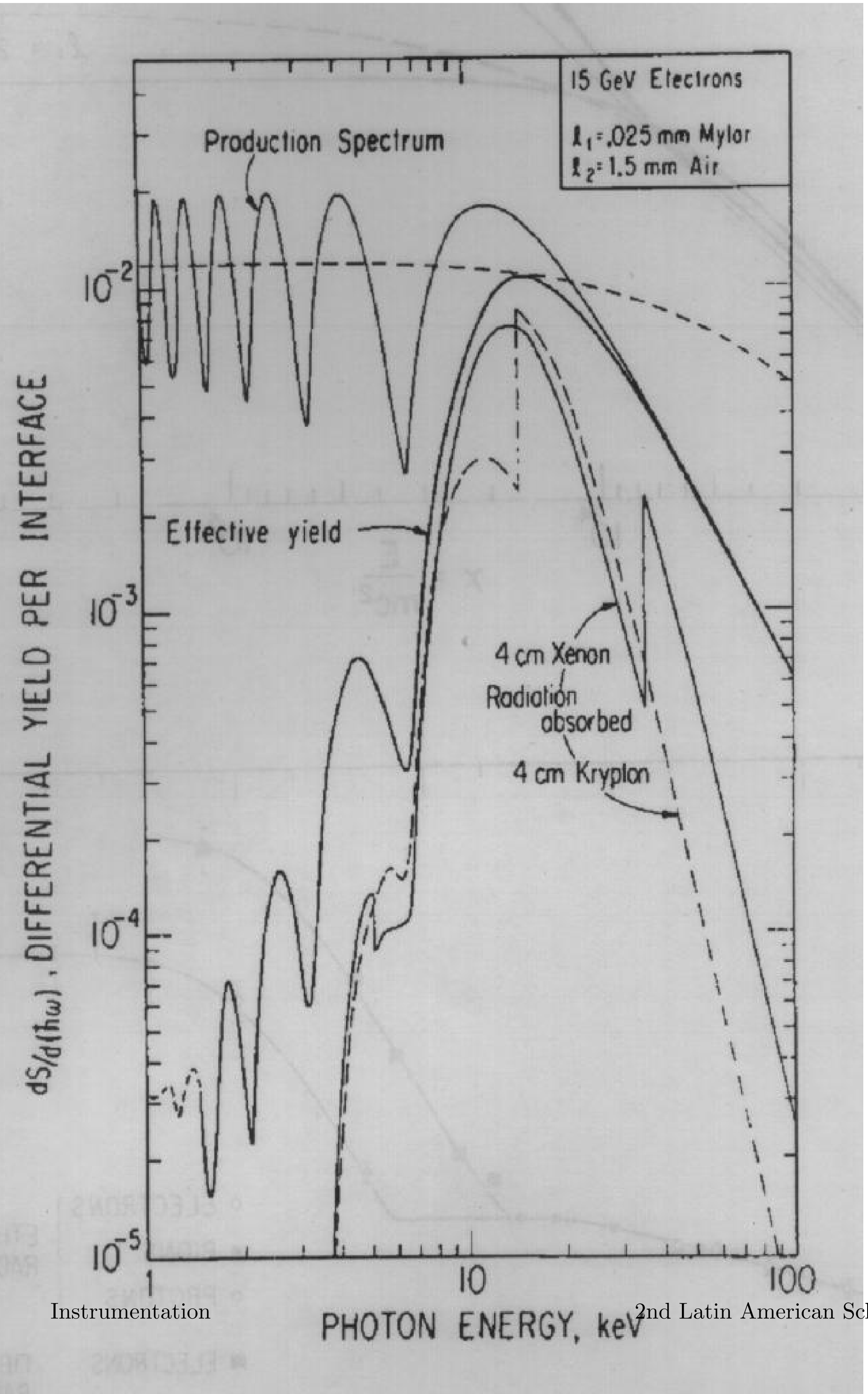
$$S = \frac{\alpha \hbar z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma$$

$\alpha = 1/137$, ω_1, ω_2 plasma frequencies, $\gamma = E/mc^2$.
Typical values: Air $\omega_1 = 0.7\,\mathrm{eV}$, polypropylene $\omega_2 = 20\,\mathrm{eV}$

Spectral and angular dependence of Transition Radiation:

$$\frac{d^2}{d\vartheta d\omega} = \frac{2e^2}{\pi c} \left(\frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_1^2/\omega^2} - \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_2^2/\omega^2} \right)^2$$

$\Longrightarrow$ Most of radiation in cone with half angle $1/\gamma$: forward in particle direction.



- Large photon energies $\omega > \gamma\omega_2 \approx 20 - 30\,\mathrm{KeV}$: large drop of intensity $\propto \gamma^4/\omega^4$
- Medium energies $\gamma\omega_1 < \omega < \gamma\omega_2$: Logarithmic decrease with ω
- Small energies $\omega < \gamma\omega_1 \approx 1\,\mathrm{KeV}$: intensity almost constant

Probability to emit a KeV photon: $\approx 10^{-2} \Longrightarrow$ Need a lot of interfaces: stack of radiator foils.
Consequences:

- Need minimum foil thickness so particle field reaches new equilibrium
- Transition $\omega_1 \rightarrow \omega_2$ and $\omega_2 \rightarrow \omega_1$ equal $\Longrightarrow$ Interference effects (min and max in fig)
- Equally spaced foils: Interference between amplitude of different foils
- Finite thickness of foils: re-absorption of radiation ($\propto Z^5$): Low Z materials.

Typical values used in TRDs:
Thickness: $30\,\mu$m, distance: $300\,\mu$m,
materials: mylar, CH_2, carbon fibers, lithium.

Detection of Transition Radiation

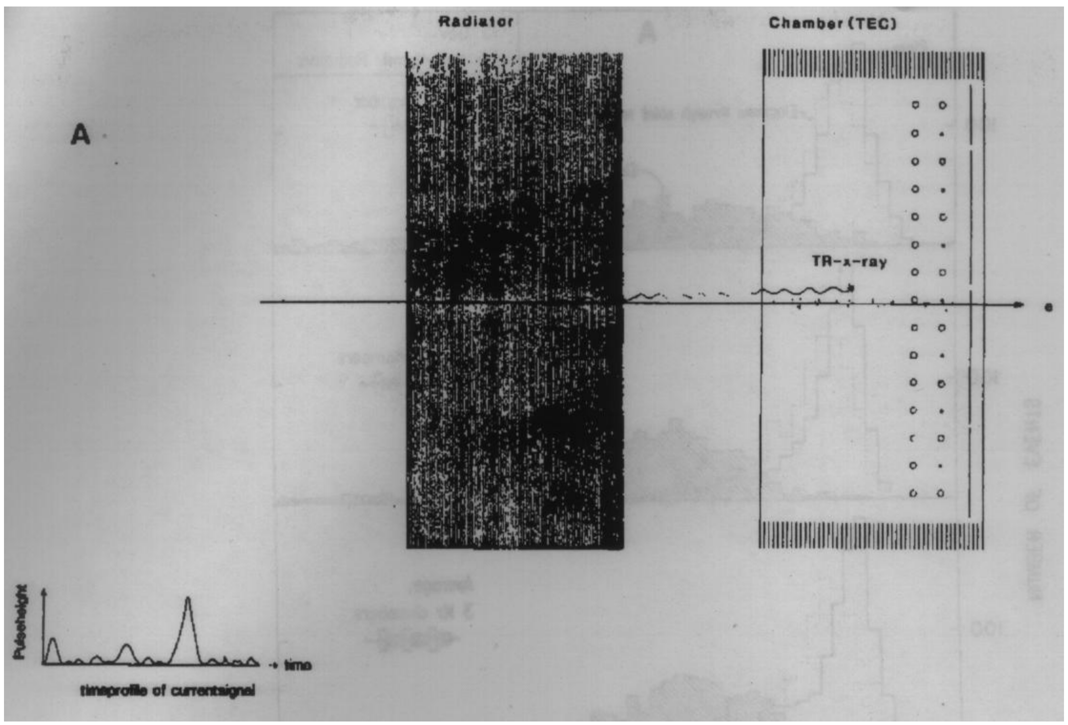
X-rays emitted under small angle to particle track

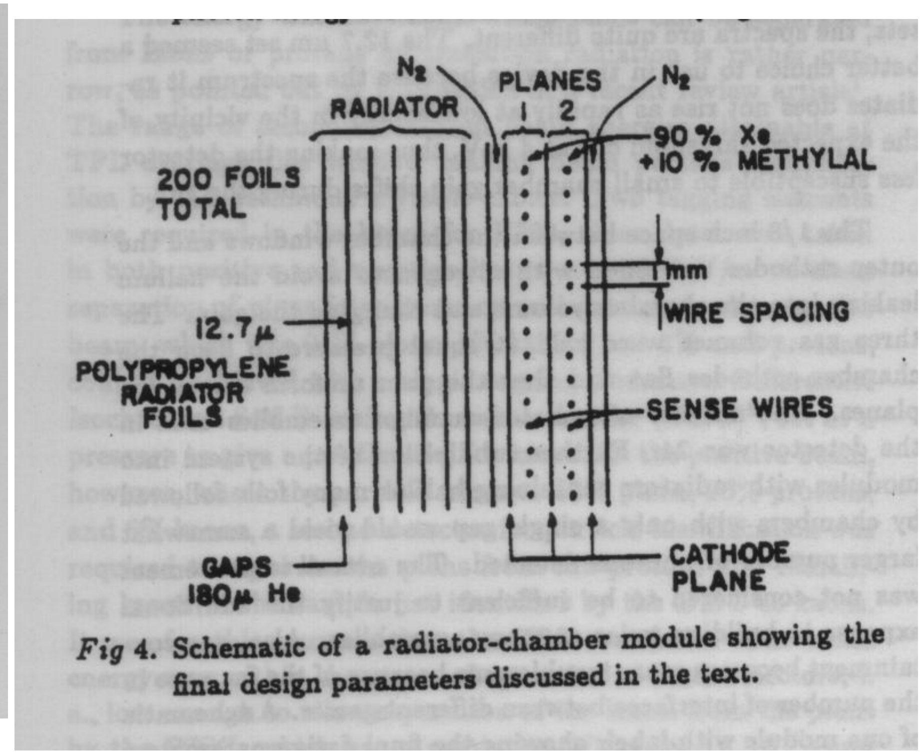
$\Longrightarrow$ X-ray detector sees X-rays and particle dE/dx together.

Typical dE/dx in gas detectors: some KeV/cm and Landau distributed

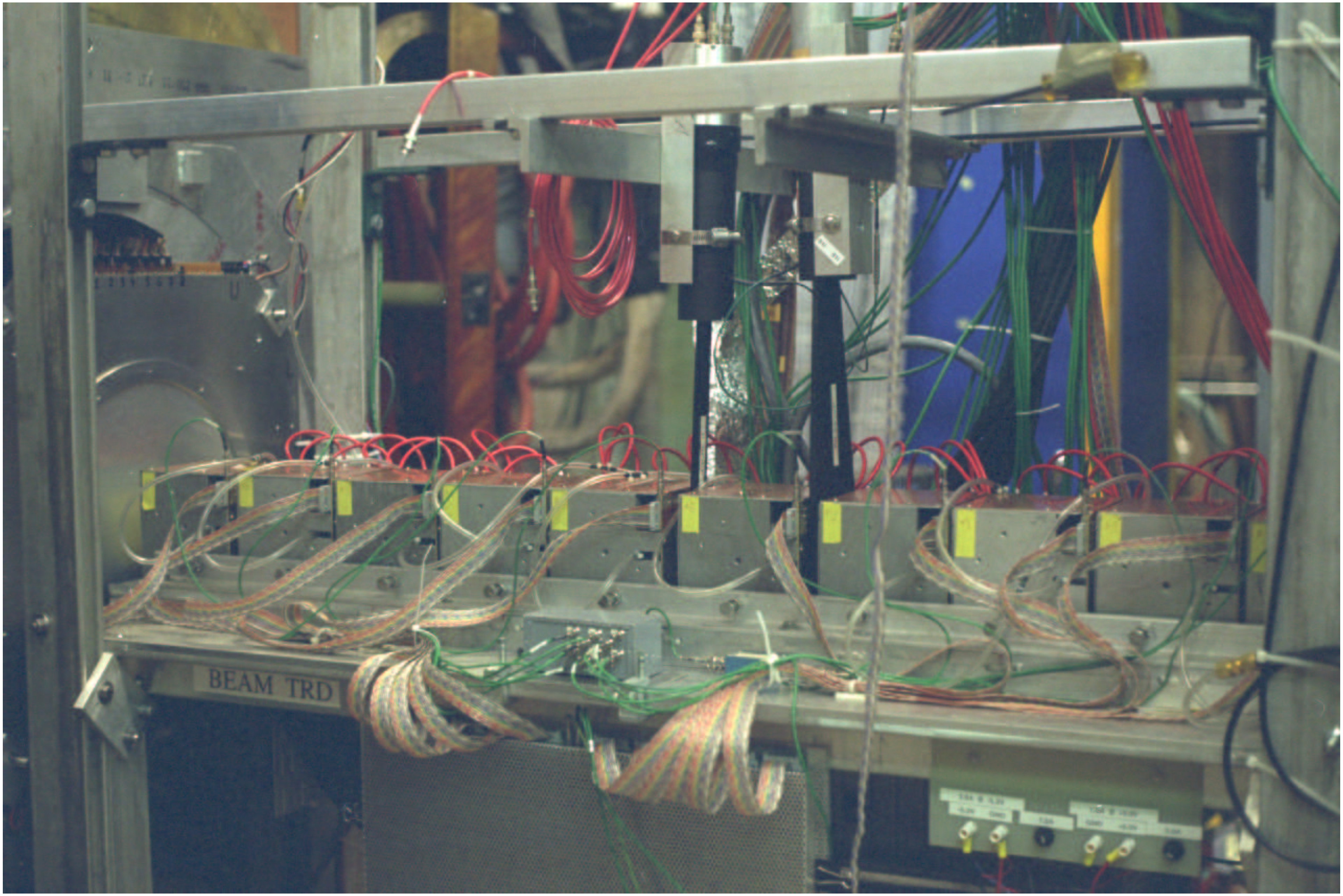
$\Longrightarrow$ Signals from dE/dx and X-ray similar

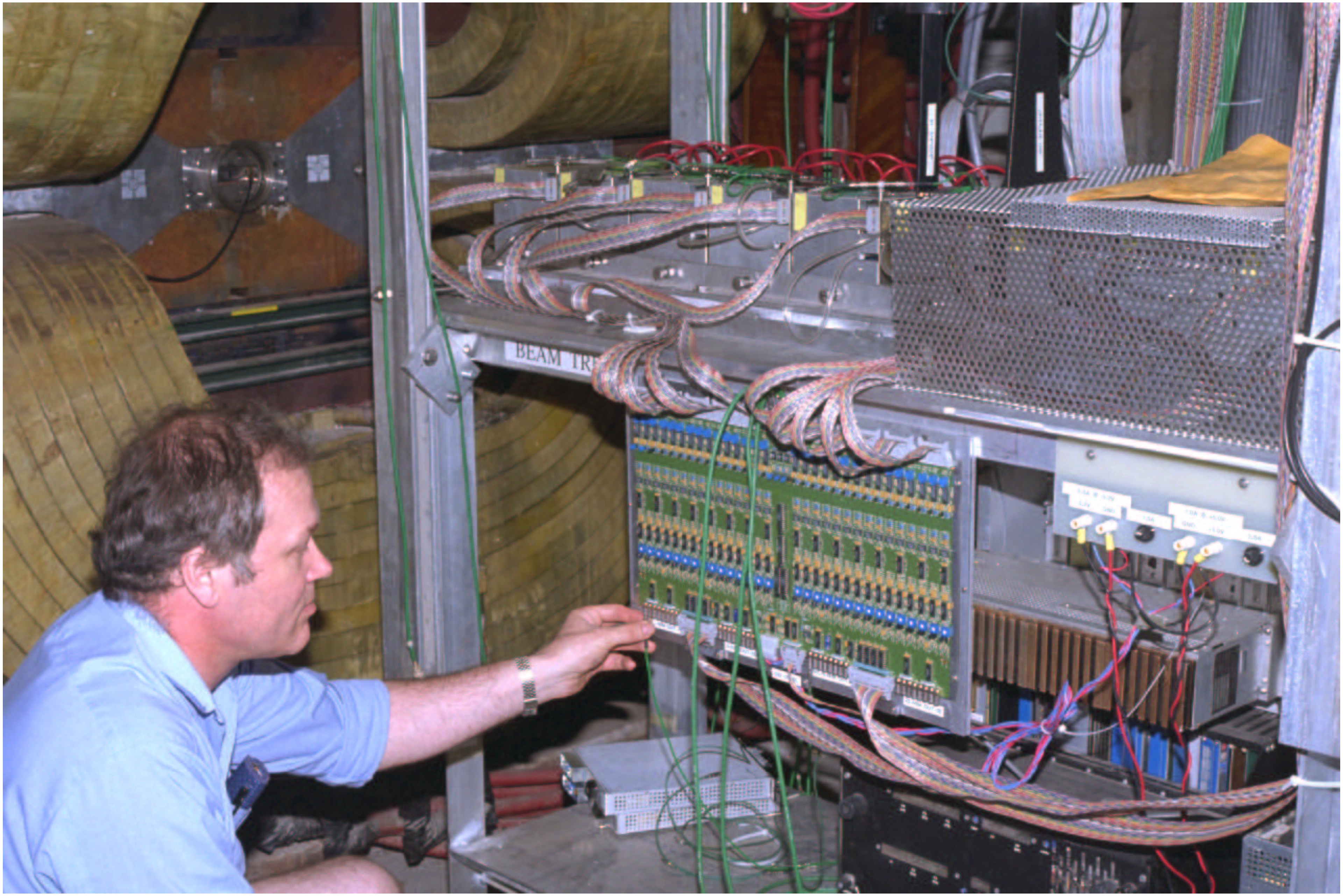
Detector: Use "thin" MWPC, with Xenon or Krypton, several (10) radiator / chamber units to beat Landau



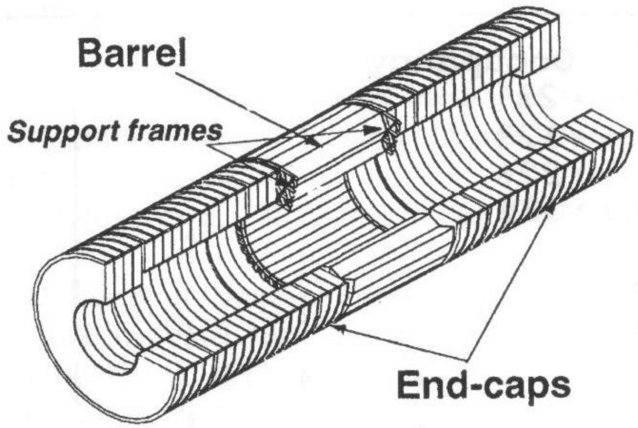


Two identification methods: Charge integration, Cluster counting


BEAM TRD


BEAM TR

ATLAS Transition Radiation Tracker (TRT)



Length:	Total	6802 cm	N straws:	Total	372032
	Barrel	148 cm		Barrel	52544
	End-cap	257 cm		End-cap	319488
Outer diameter		206 cm	N electronics channels		424576
Inner diameter		96-128 cm	Weight		~ 1500 kg

Fig. 11. ATLAS Transition Radiation Tracker (TRT) conceptual design [2].

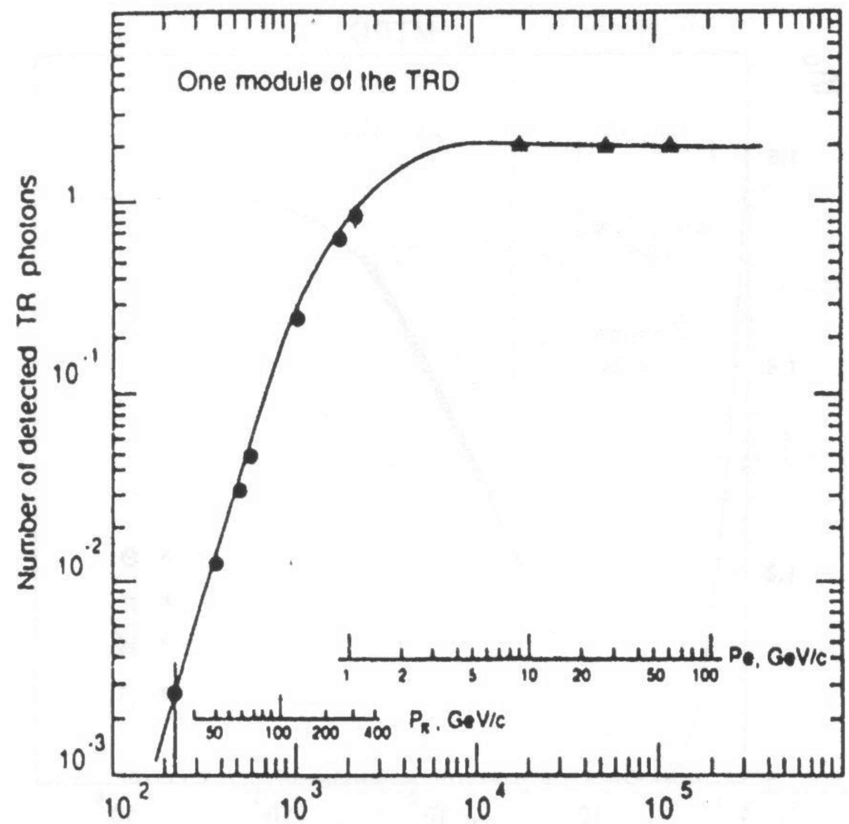


Fig. 8. The detected number of the TR photons for different Lorentz factors [4].

Cherenkov Radiation

A charged particle with a velocity v larger than the velocity of light in a medium emits light.

Angle of emission:
$$\cos\theta_c = \frac{1}{\beta\, n} = \frac{1}{\frac{v}{c}\, n}$$

Number of photons:
$$\frac{d^2N}{dEdl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$
$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

First (obvious) application: Threshold Cherenkov Detectors

For fixed momentum and only 2 particles to separate (beam line)

More than 2 particles and/or wider momentum range: Several counters at different thresholds

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PHOTO-IONIZATION AND CHERENKOV RING IMAGING

J. SEGUINOT* and T. YPSILANTIS†

CERN, Geneva, Switzerland

Received 17 December 1976

We have investigated the photo-ionization process in gases and shown that single photon pulse counting in multiwire proportional chambers (MWPC) is possible with about 50% quantum efficiency for photons above 9.5 eV. An application of this technique in imaging the Cherenkov ultra-violet (UV) radiation is presented.

1. Introduction

The Cherenkov radiation effect in an optical medium allows a precise determination of the velocity β [or $\gamma = (1-\beta^2)^{-\frac{1}{2}}$] of a charged particle passing through the medium. From the Cherenkov relation[1])

$$\cos\theta = 1/\beta n, \tag{1}$$

where θ is the emission angle of the Cherenkov light and n the refractive index of the optical medium, we find

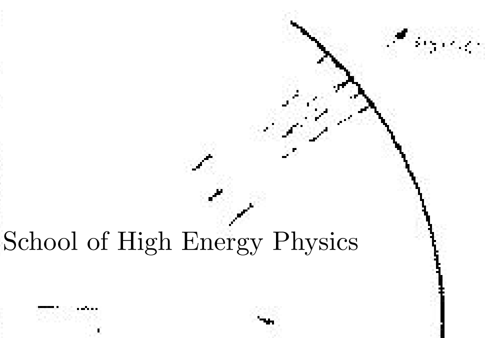
$$\frac{\Delta\beta}{\beta} = \left[\tan^2\theta\,(\Delta\theta)^2 + \left(\frac{\Delta n}{n}\right)^2\right]^{\frac{1}{2}}, \tag{2}$$

with $\Delta\beta$, $\Delta\theta$ and Δn the r.m.s. error in the measurement of β, θ and n respectively. Litt and Meunier[2]) show that with a "differential isochronous self collimating" type Cherenkov counter (DISC) a resolution of $\Delta\beta/\beta \approx 10^{-7}$ is possible. This corresponds to a γ resolution of $\Delta\gamma/\gamma = \gamma^2\,\Delta\beta/\beta = 0.4\%$ at $\gamma = 200$. In such counters the Cherenkov photons emitted at different points along the particle's straight line trajectory are focused by a reflective mirror (radius R, focal length $f = \frac{1}{2}R$) to give a circular ring image (radius r) at the mirror focal plane. In the small angle approximation the focal surface is a plane and the radius of the ring image is

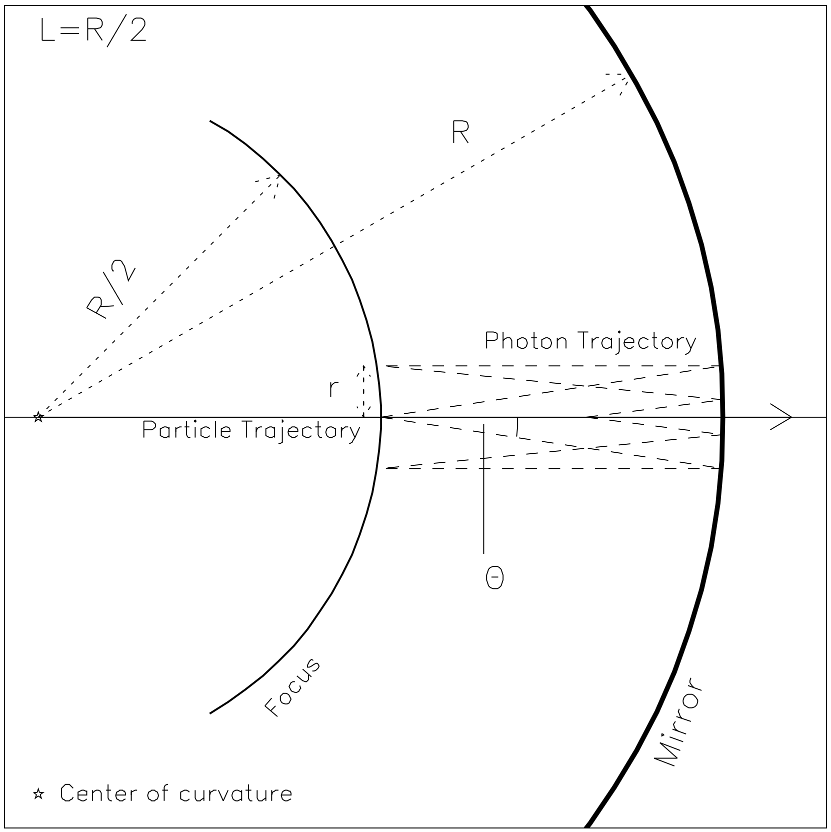
$$r = f\tan\theta, \tag{3}$$

the emitted photons. Obviously a DISC type counter can only be used in collimated beams so that the source of Cherenkov radiation is along the optical axis of the device. Furthermore, the counter is not continuously sensitive in β and responds only to particles having a preset value of β (i.e. Cherenkov light which passes through the annulus). Such counters are suitable for velocity (mass) selection in collimated (momentum analyzed) primary particle beams but completely unsuitable for velocity measurement of secondary particles emerging from an interaction. The phase space occupied by these particles is large whereas the phase space acceptance of DISC is small.

A secondary particle detector may be imagined (see fig. 1) as consisting of a spherical mirror of radius R whose centre is the source of secondary particles (target) and a spherical detector surface at radius $\frac{1}{2}R$ with the Cherenkov radiating medium



Ring Imaging Cherenkov – The Basics



$$\cos\theta_c = \frac{1}{\beta \cdot n}$$

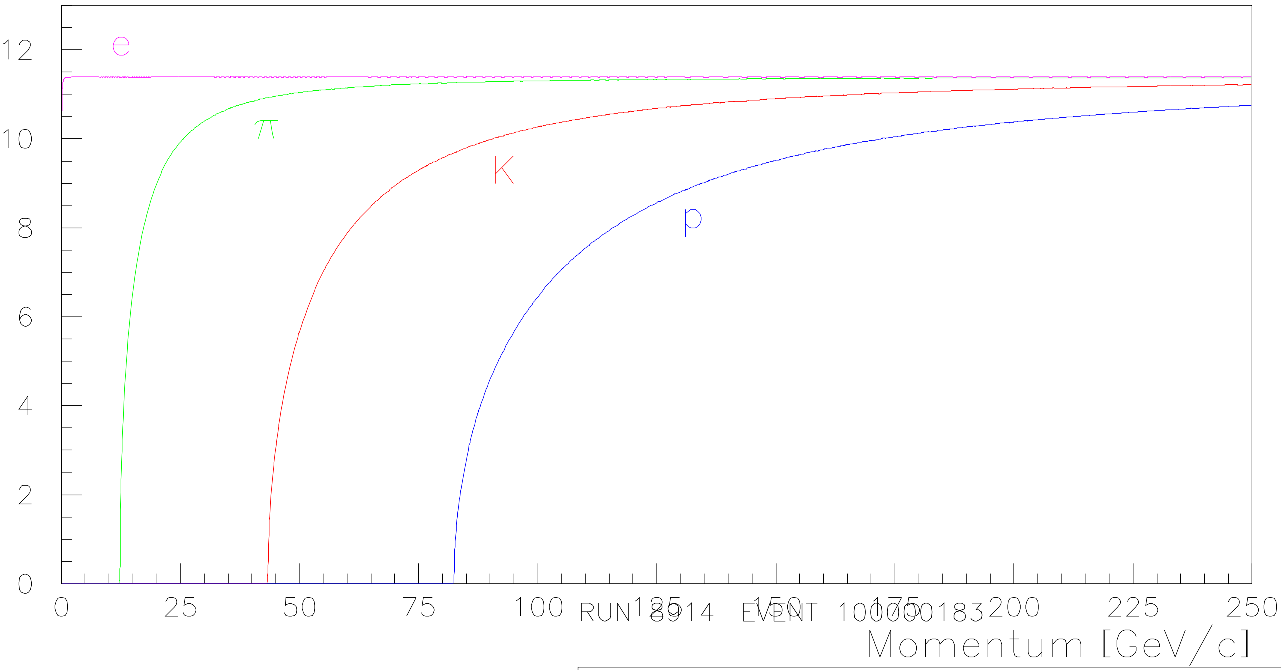
$$r = F \cdot \theta_c = \frac{R}{2} \cdot \theta_c$$

$$N_{ph} = N_0 \cdot L \cdot \sin^2\theta_c$$

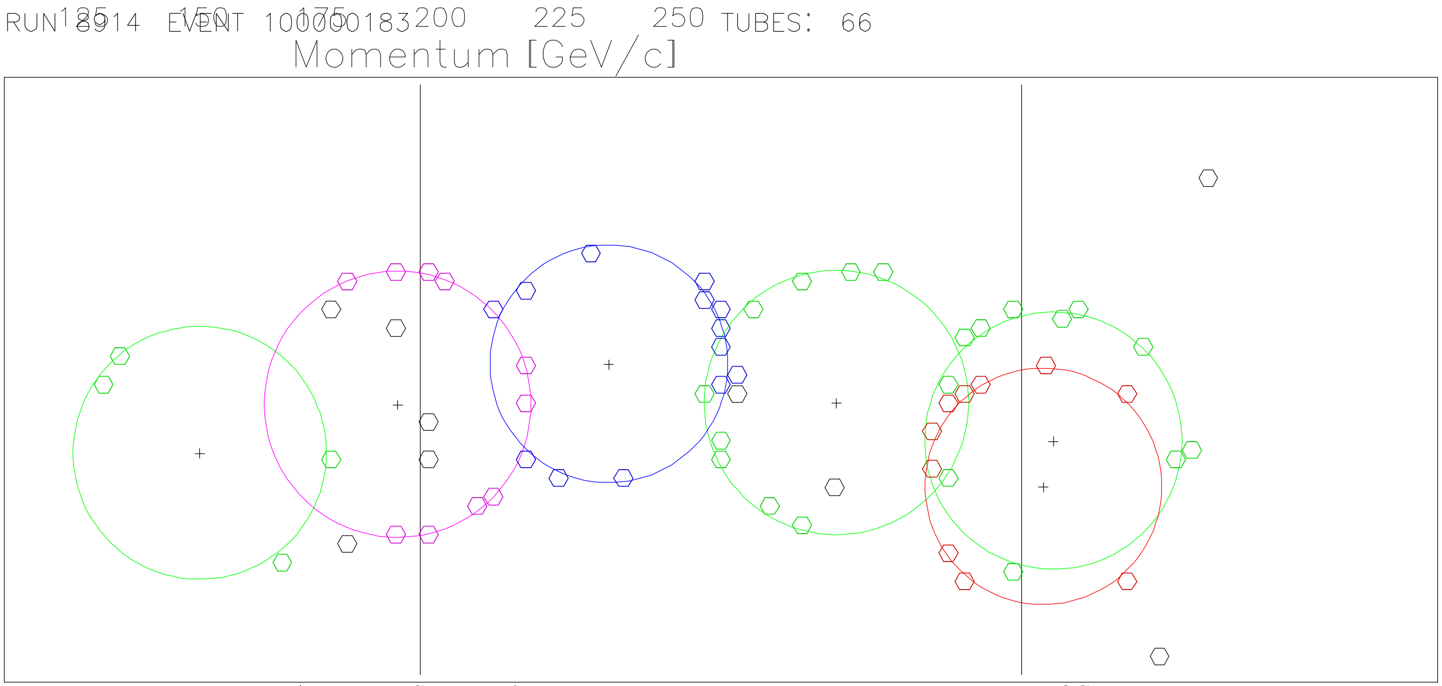
θ_c: Cherenkov angle
β: velocity
n: refractive index
r: Radius of ring on focal surface
R: Radius of curvature of spherical mirror(s)
F: Focal length ($F = R/2$)
L: Radiator length (usually $L = F$)

Parallel particles have the same ring image

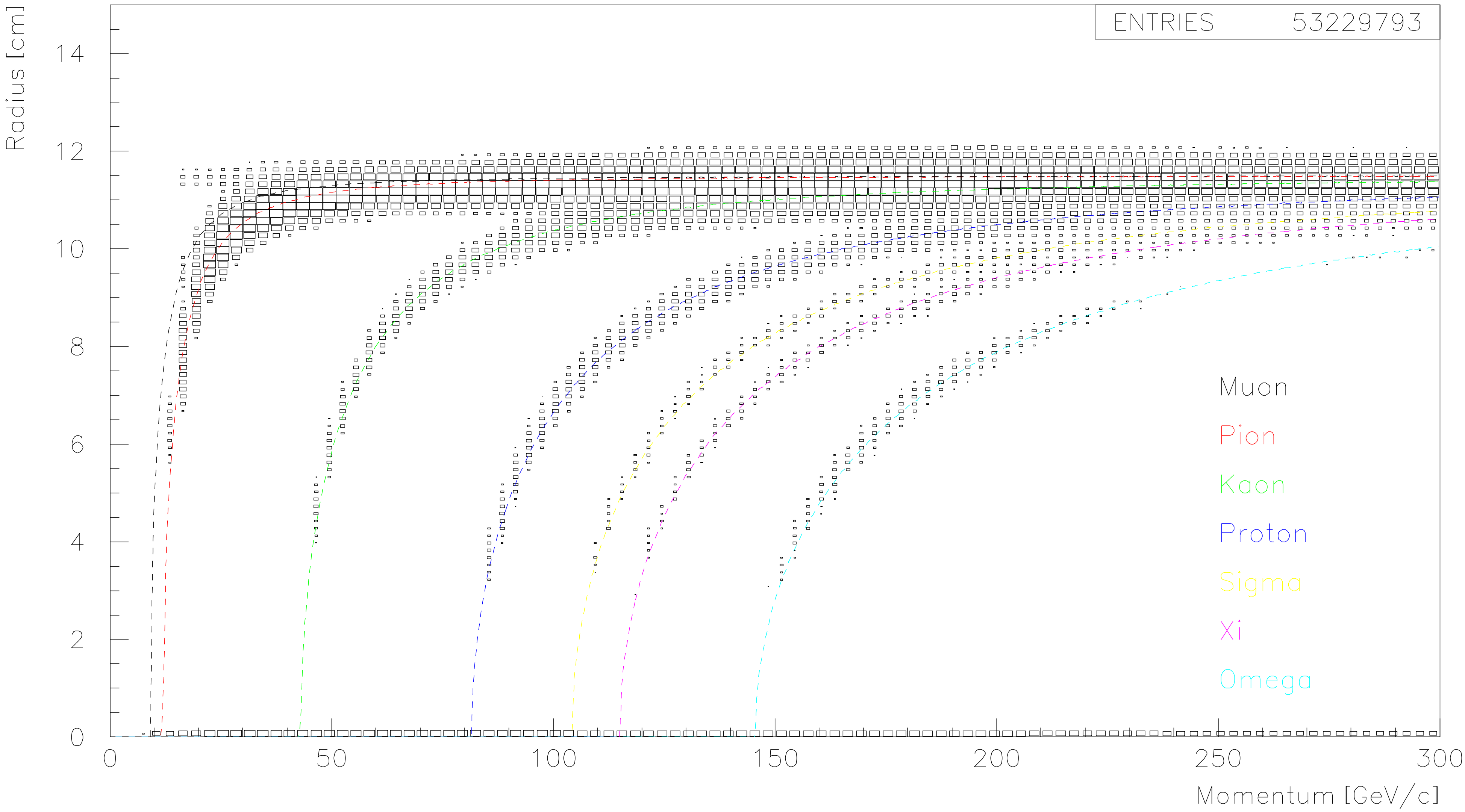
Cherenkov Radii – Neon Radiator, F= 1000cm



$$r = \frac{R}{2}\sqrt{2 - \frac{2}{n}\sqrt{1 + \frac{m^2c^2}{p^2}}}$$



SELEX RICH: Particle Id negative tracks



Short History of RICHes

First Generation: Beginning of 1980's.
Examples: Omega RICH (WA69, WA82), E653 RICH.

Second Generation: End-of 80's beginning of 90's.
Examples: Upgraded Omega RICH (WA89, WA94), Delphi, SLD–GRID, CERES.

Third Generation: Mid-End 90's.
Examples: SELEX RICH, Hermes, Hera-B.

New Generation: BaBar–DIRC, PHENIX, CLEO–III, COMPASS

Future: ALICE, LHC–B, BTeV, CKM, ...

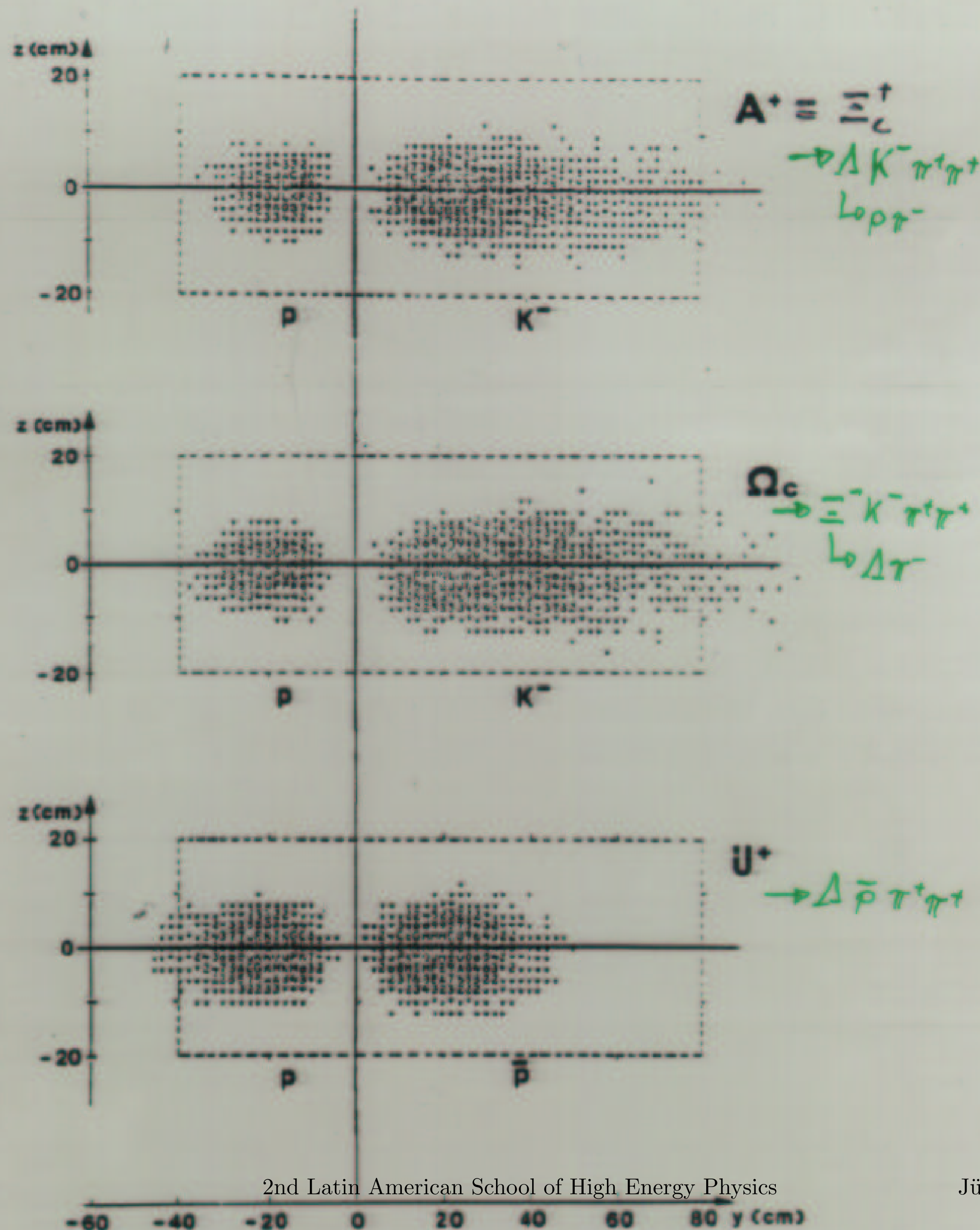
RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (up to 100000 or more)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2\theta_c$$

  $\Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Detection of UV-photons: convert photon in electron (photoeffect)
  1. small (up to a few thousand) number of pixels: Photomultipliers
  2. large number of pixels or area: Time Expansion Chambers with TEA or TMAE
- When using TEC: particle pass through the chambers: dE/dx
- When using TEC: response (memory) time limit rate

Distribution of Ring Centers

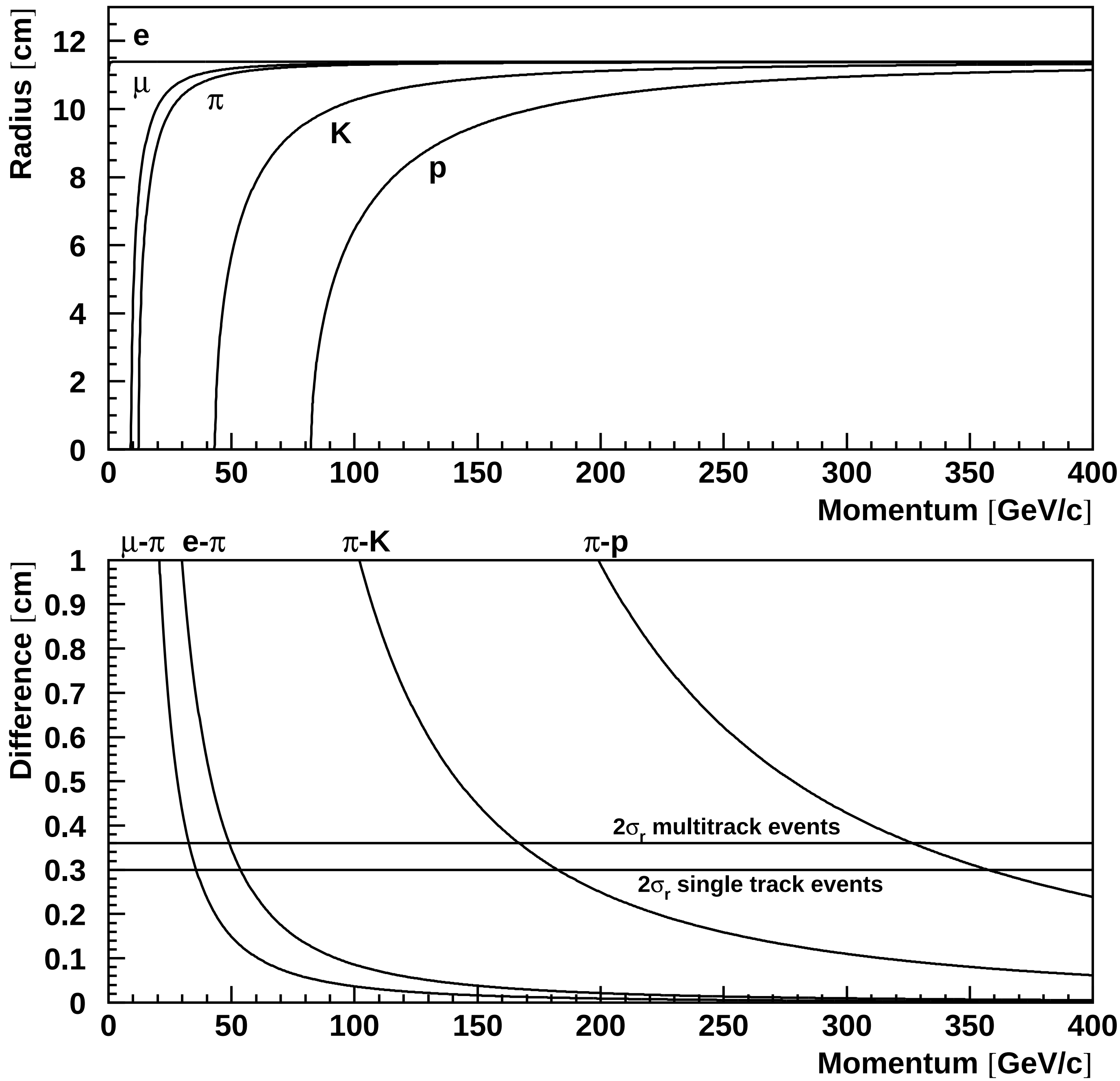


RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface (up to square meters)
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (up to 100000 or more)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2\theta_c$$

  $\Longrightarrow$ Ultraviolet
- refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
- Detection of UV-photons: convert photon in electron (photoeffect)
  1. small (up to a few thousand) number of pixels: Photomultipliers
  2. large number of pixels or area: Time Expansion Chambers with TEA or TMAE
- When using TEC: particle pass through the chambers: dE/dx
- When using TEC: response (memory) time limit rate



e
μ
π
K
p
Radius [cm]
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400
Momentum [GeV/c]
μ-π
e-π
π-K
π-p
Difference [cm]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2σr multitrack events
2σr single track events
0
50
100
150
200
250
300
350
400
Momentum [GeV/c]

RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface (square meters)
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (100000)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2\theta_c$$

  $\Longrightarrow$ Ultraviolet
- Refractive index $n = n(\lambda) \Longrightarrow$ Chromatic dispersion
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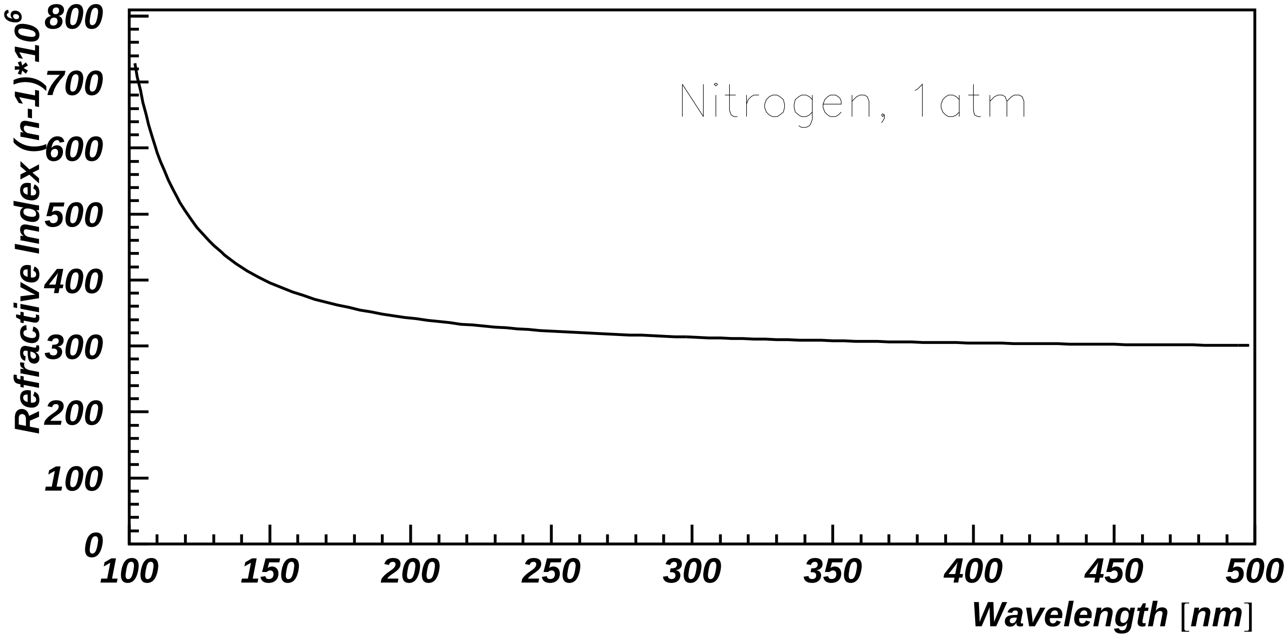
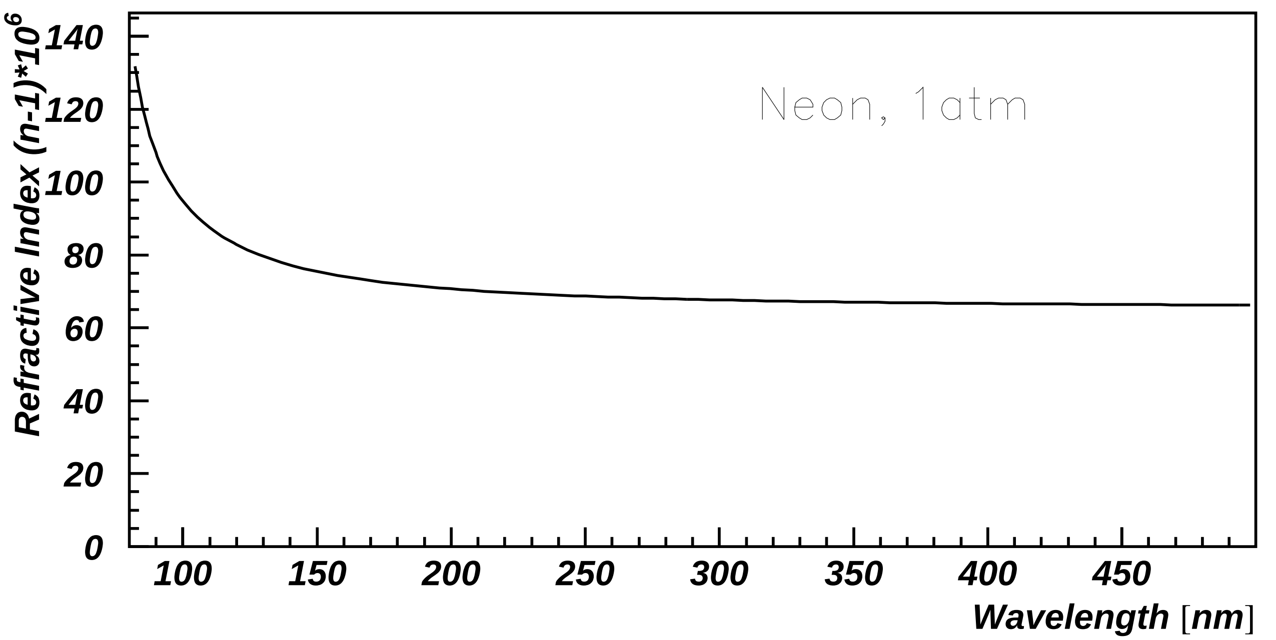

Nitrogen, 1atm
Refractive Index (n-1)*10^6
0
100
200
300
400
500
600
700
800
100
150
200
250
300
350
400
450
500
Wavelength [nm]


Neon, 1atm
Refractive Index (n-1)*10^6
0
20
40
60
80
100
120
140
100
150
200
250
300
350
400
450
Wavelength [nm]

RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface
- good resolution of photon position $\Longrightarrow$ large number of “pixels” (100000)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2 \theta_c$$

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- When using TEC: response (memory) time limit rate

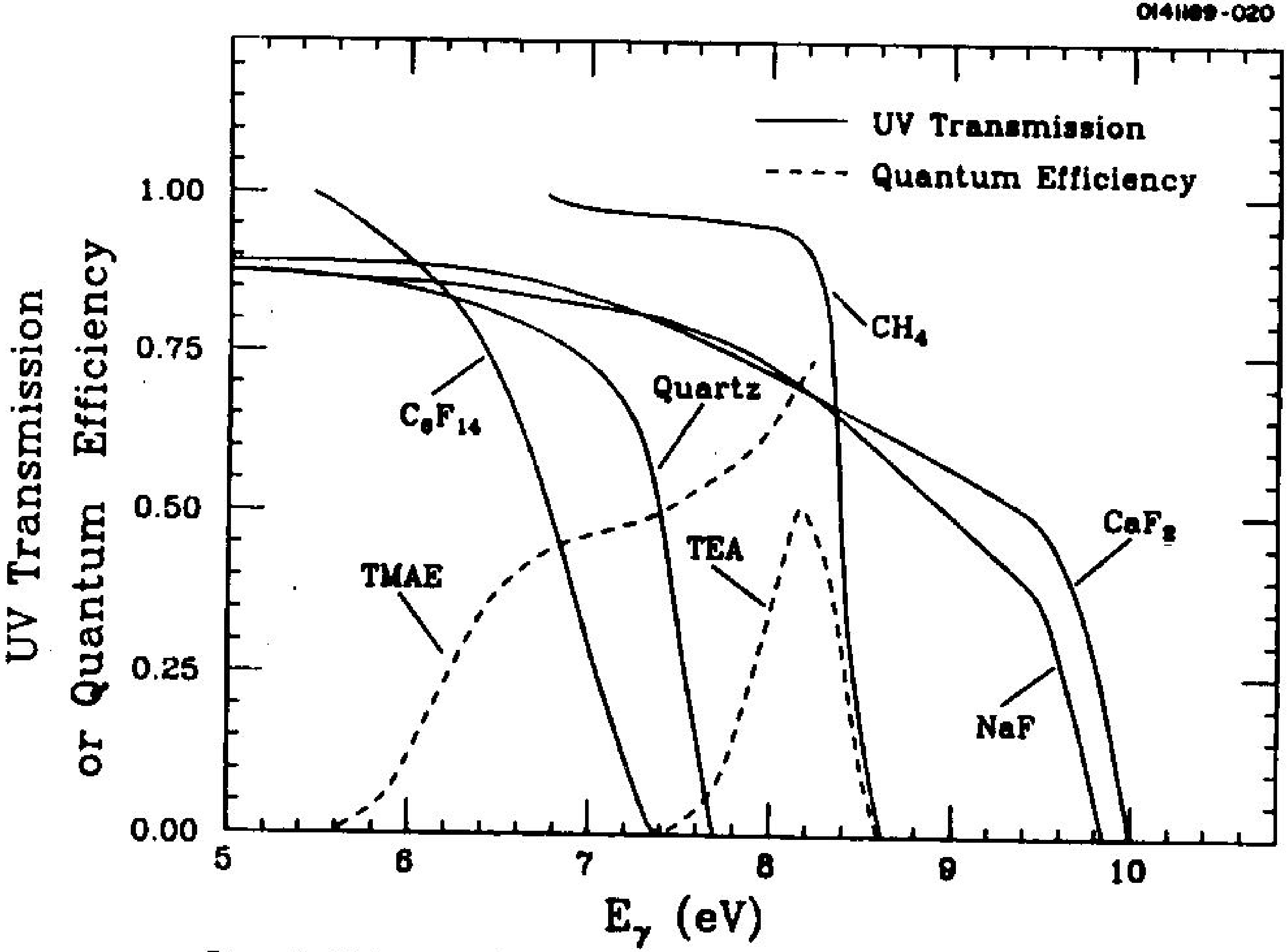
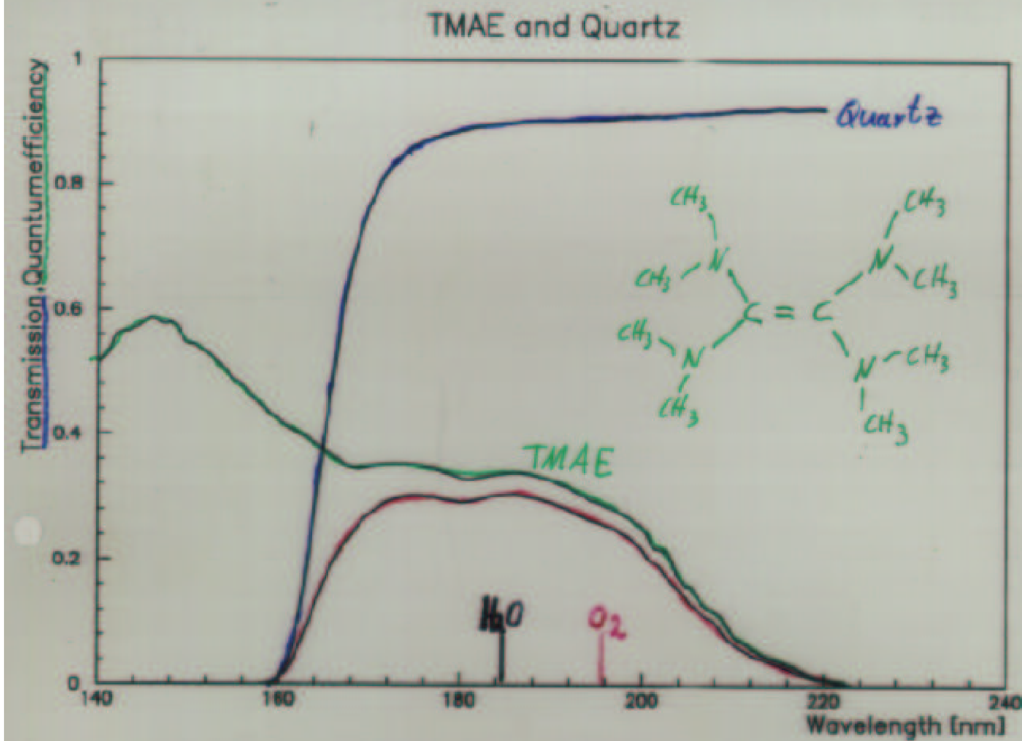


Figure 13: Photon transmission and photoionization quantum efficiency for various CRID materials as function of photon energy in the UV range. (Reproduced from

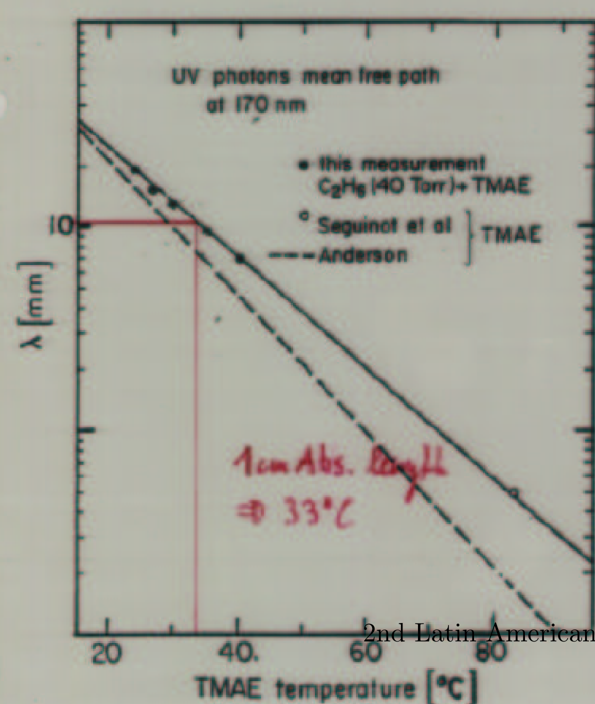


TMAE:

$E_{ion} = 5.3\,eV$

very reactiv with O_2

low vapour pressure



⇒ heat detector!

to > 40°C (105°F)

RICH – The Reality

- Center of ring depends on track angle $\Longrightarrow$ large detector surface
- good resolution of photon position $\Longrightarrow$ large number of "pixels" (100000)
- Spectrum of Cherenkov photons

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha}{\lambda^2} L \sin^2\theta_c$$

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- When using TEC: particle pass through the chambers: dE/dx
- When using TEC: response (memory) time limit rate

First RICH Example: The Omega RICH

WA89: A Hyperon Beam Experiment at the CERN-SPS Using the Omega Facility

Bologna Univ./INFN, CERN, Genoa Univ./INFN Grenoble Univ./IN2P3, Heidelberg MPI, Heidelberg Univ., Mainz Univ., Moscow Lebedev Phys. Inst.

Bologna

A. Forino, R. Gessaroli, P Mazzanti, A. Quareni-Vignudelli, F. Viaggi

CERN

F. Antinori, W. Beusch, J.P. Dufey, B.R. French, P. Grafström

Genoa Univ./INFN

M. Dameri, R.B. Hurst, B. Osculati, L. Rossi, G. Tomasini

Grenoble Univ./IN2P3

D. Barberis, C. Bérat, M. Buénerd, F. Charignon, J. Chauvin, J.T. Hostachy, Ph. Martin, M. Rey–Campagnolle, R. Touillon

Heidelberg MPIfK

E. Albertson, K.-H. Brenzinger, W. Brückner, F. Dropmann, S.G. Gerassimov, M. Godbersen, T. Kallakowsy, R. Michaels, S. Paul, B. Povh, K. Röhrich, A. Trombini, A. Wenzel, R. Werding

Heidelberg Univ.

J. Engelfried, F. Faller, J. Heintze, S. Kluth, S. Ljungfelt, P. Lennert, K. Martens, H. Rieseberg, H.-W. Siebert, A. Simon, G. Wälder

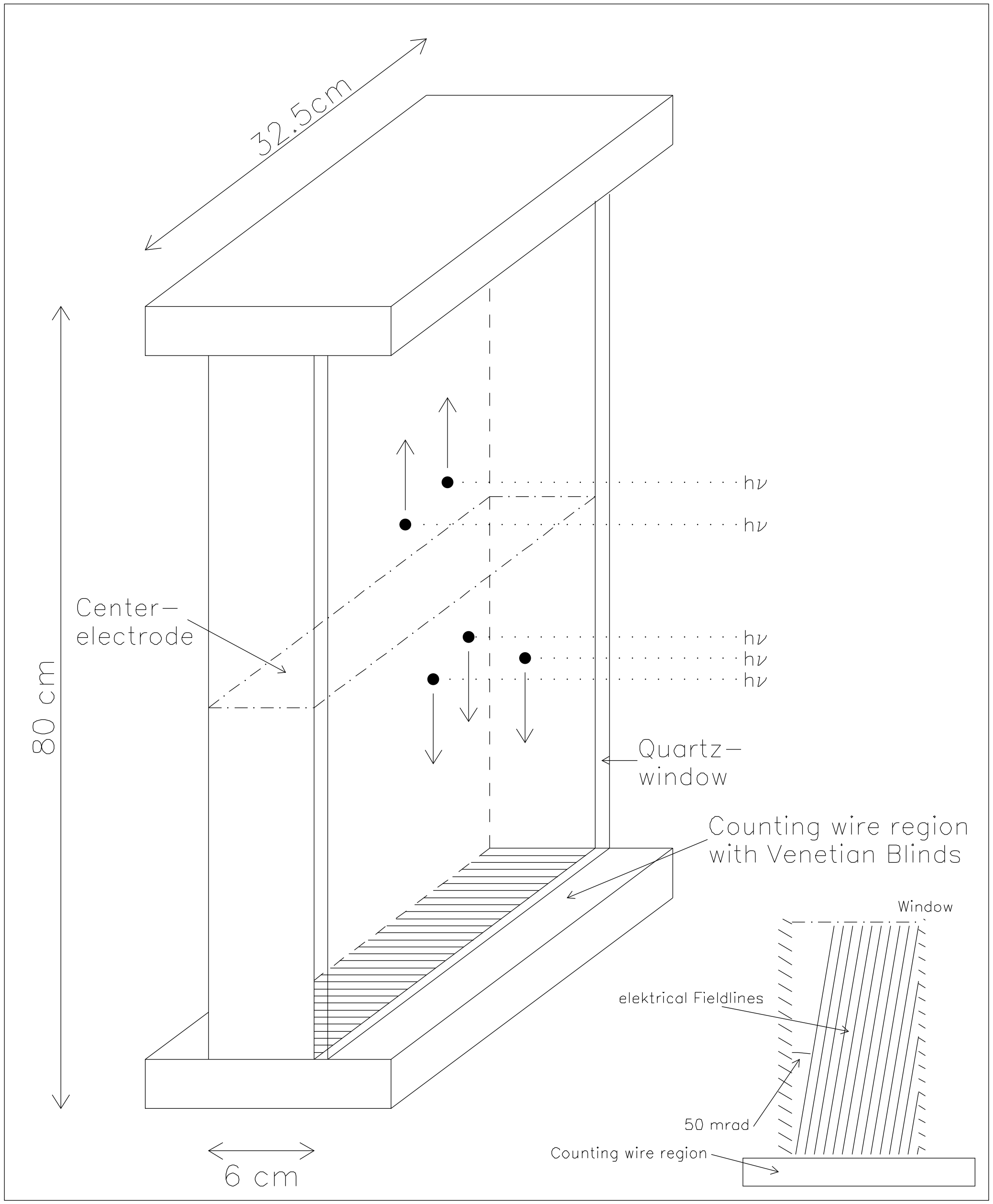
Mainz Univ., Inst. of Nucl. Physics

E. Chudakov, U. Müller, G. Rosner, H. Rudolf, B. Volkemer, Th. Walcher

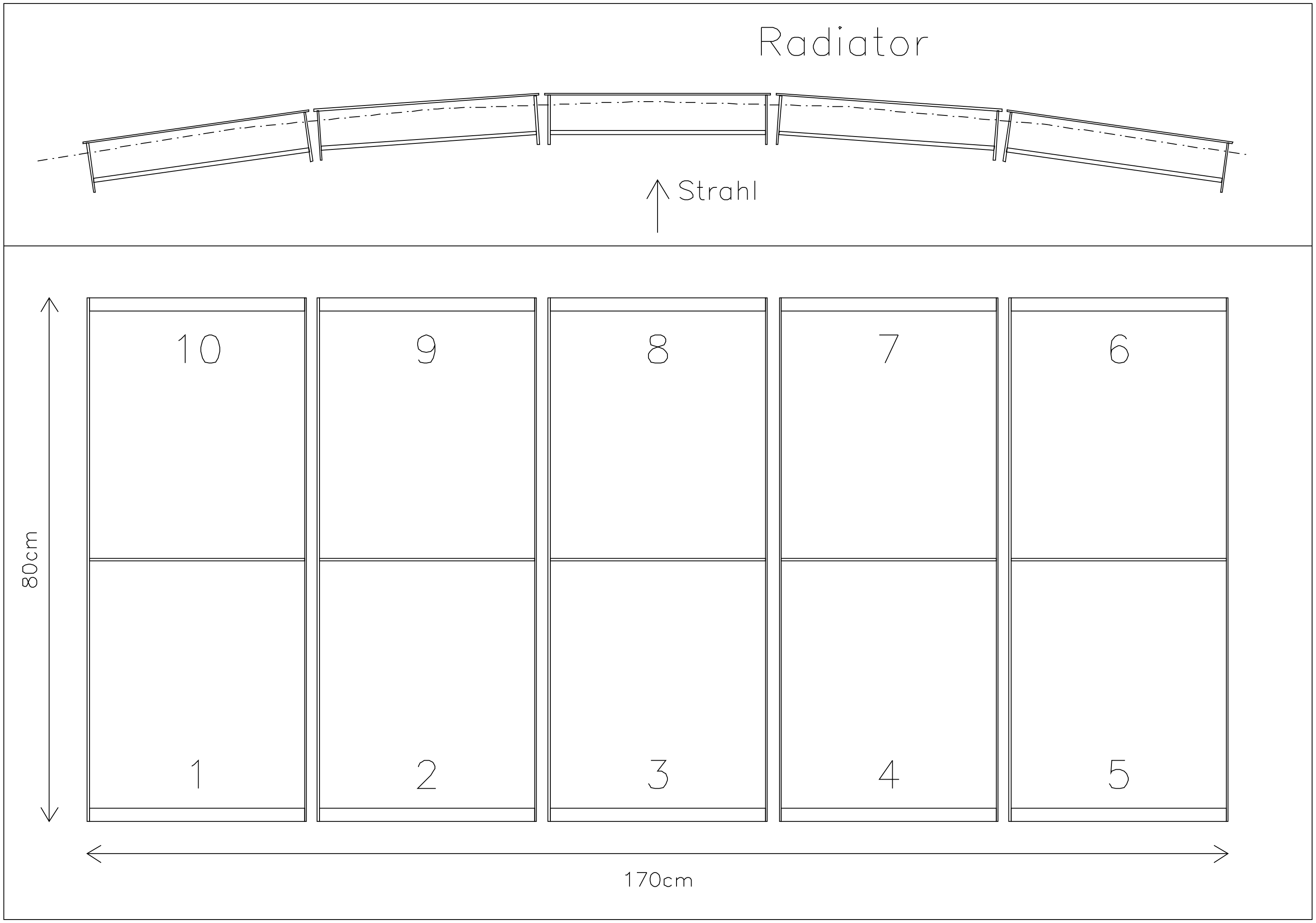
Moscow Lebedev Phys. Inst.

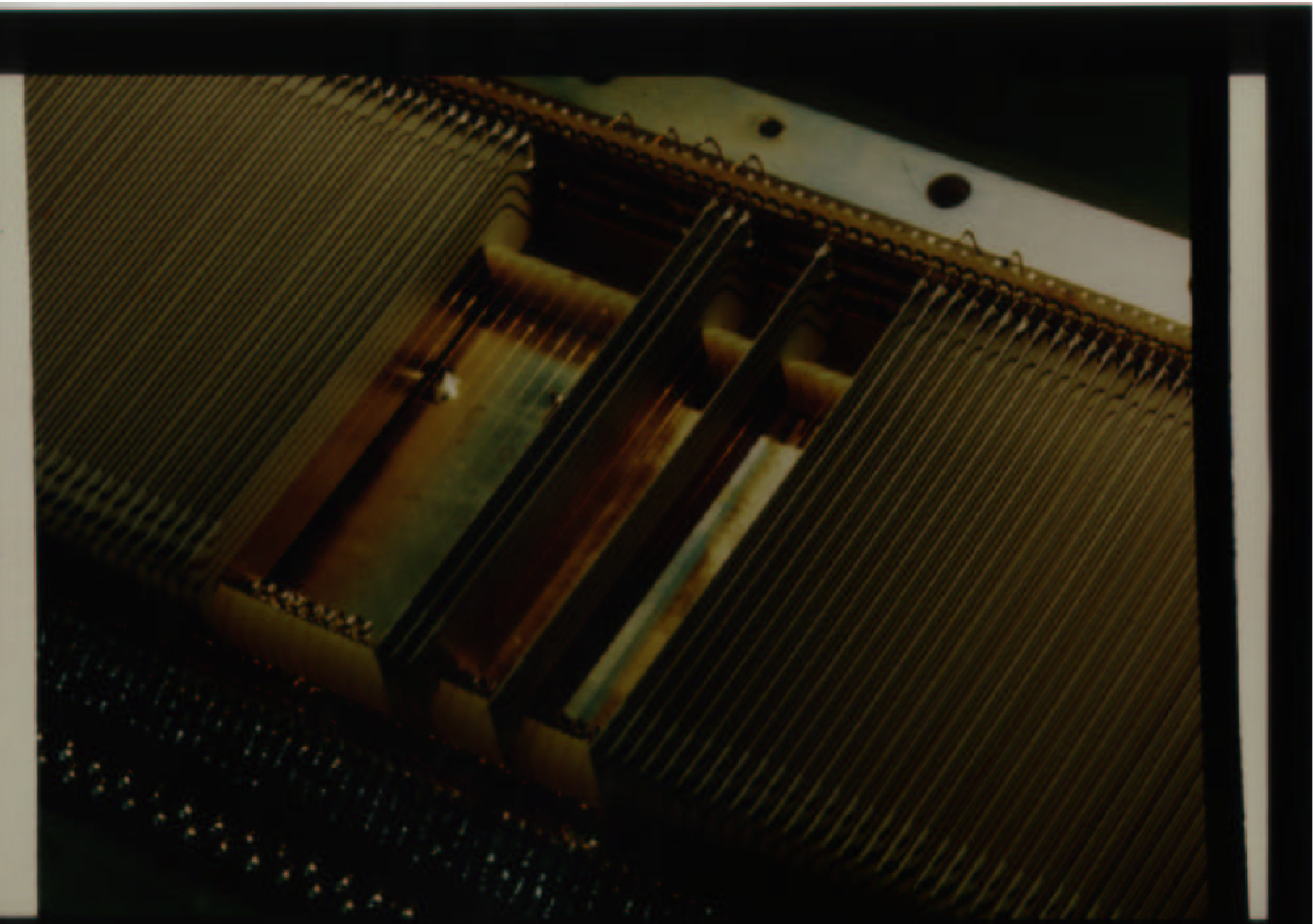
M.I. Adamovich, Yu.A. Alexandrov, S.P. Kharlamov, L.N. Malinina, N.G. Peresadko, M.V. Zavertyaev

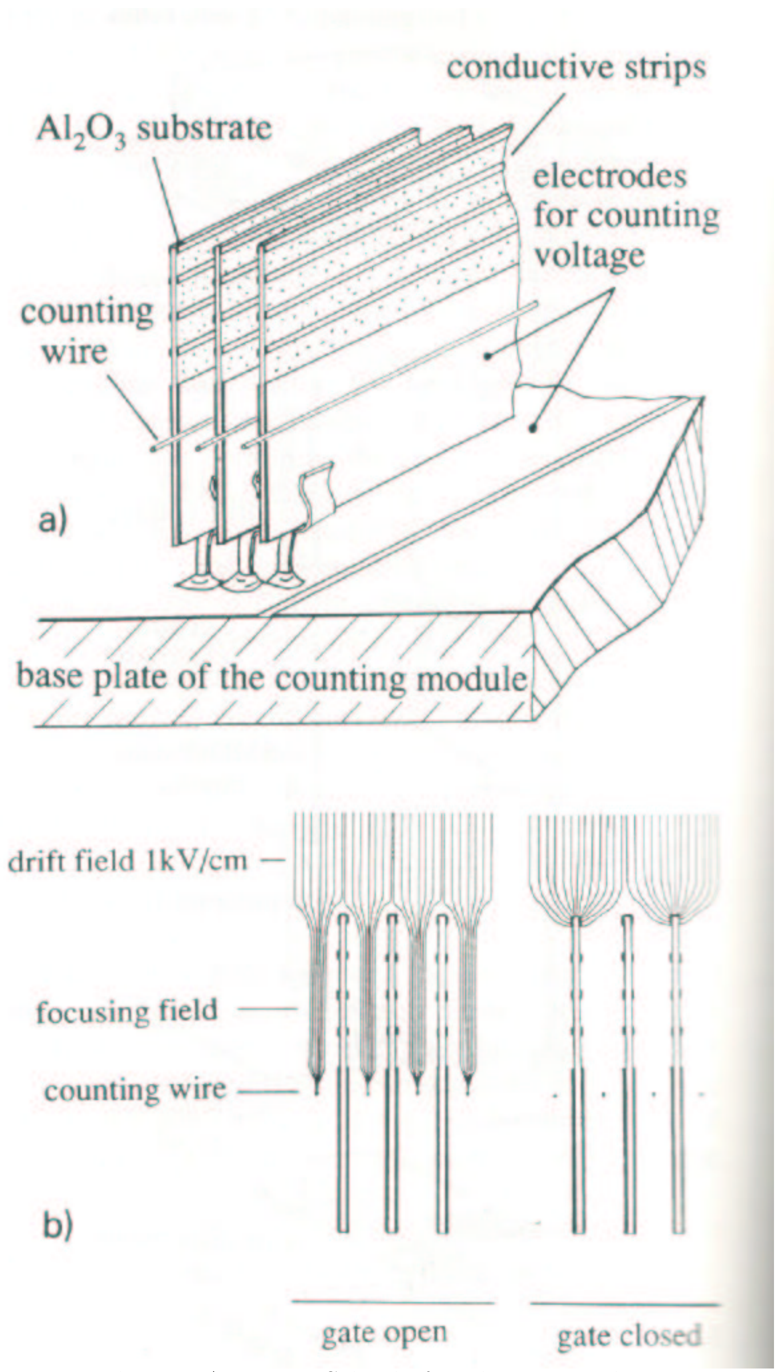
RICH Group



Counting gas: Ethan + TMAE,
1 KV/cm, 5 cm/μsec


Radiator
Strahl
10
9
8
7
6
1
2
3
4
5
80cm
170cm




conductive strips
Al_2O_3 substrate
electrodes
for counting
voltage
counting
wire
a)
base plate of the counting module
drift field 1kV/cm
focusing field
counting wire
b)
gate open
gate closed

Particle Identification Algorithm

- only discrete particle masses: e, μ, π, K, p, Σ, etc.
- Track parameter and momentum known
  $\Longrightarrow$ Calculate ring radius for each hypothesis
- "Compare" measured and expected rings for each hypothesis with a maximum likelihood method
- for identification, make cuts on likelihood ratios

published in:

U.Müller, J.Engelfried et al.:

Particle identification with the RICH detector in experiment WA89 at CERN.

Nucl. Instr. Meth. **A 343** (1994) 279-283.

Second RICH Example: The SELEX RICH

The SELEX Collaboration

G.P. Thomas
Ball State University, Muncie, IN 47306, U.S.A.

E. Gülmez
Bogazici University, Bebek 80815 Istanbul, Turkey

R. Edelstein, S.Y. Jun, A.I. Kulyavtsev[1], A. Kushnirenko, D. Mao[1], P. Mathew[2], M. Mattson, M. Procario[3], J. Russ, J. You[4]
Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

A.M.F. Endler
Centro Brasiliero de Pesquisas Físicas, Rio de Janeiro, Brazil

P.S. Cooper, J. Kilmer, S. Kwan, J. Lach, E. Ramberg, D. Skow, L. Stutte
Fermilab, Batavia, IL 60510, U.S.A.

V.P. Kubarovsky, V.F. Kurshetsov, A.P. Kozhevnikov, L.G. Landsberg, V.V. Molchanov, S.B. Nurushev, S.I. Petrenko, A.N. Vasiliev, D.V. Vavilov, V.A. Victorov
Institute for High Energy Physics, Protvino, Russia

Li Yunshan, Mao Chensheng, Zhao Wenheng, He Kangling, Zheng Shuchen, Mao Zhenlin
Institute of High Energy Physics, Beijing, P.R. China

M.Y. Balatz[5], G.V. Davidenko, A.G. Dolgolenko, G.B. Dzyubenko, A.V. Evdokimov, M.A. Kubantsev, I. Larin, V. Matveev, A.P. Nilov, V.A. Prutskoi, A.I. Sitnikov, V.S. Verebryusov, V.E. Vishnyakov
Institute of Theoretical and Experimental Physics, Moscow, Russia

U. Dersch[6], I. Eschrich[7], I. Konorov[8], H. Krüger[9], J. Simon[10], K. Vorwalter[11]
Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

I.S. Filimonov[5], E.M. Leikin, A.V. Nemitkin, V.I. Rud
Moscow State University, Moscow, Russia

A.G. Atamantchouk, G. Alkhazov, N.F. Bondar, V.L. Golovtsov, V.T. Kim, L.M. Kochenda, A.G. Krivshich, N.P. Kuropatkin, V.P. Maleev, P.V. Neoustroev, B.V. Razmyslovich, V. Stepanov, M. Svoiski, N.K. Terentyev[12], L.N. Uvarov, A.A. Vorobyov
Petersburg Nuclear Physics Institute, St. Petersburg, Russia

I. Giller, M.A. Moinester, A. Ocherashvili, V. Steiner
Tel Aviv University, 69978 Ramat Aviv, Israel

J. Engelfried[4], A. Morelos
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

M. Luksys
Universidade Federal da Paraíba, Paraíba, Brazil

V.J. Smith
University of Bristol, Bristol BS8 1TL, United Kingdom

M. Kaya, E. McCliment, K.D. Nelson[13], C. Newsom, Y. Onel, E. Ozel, S. Ozkorucuklu, P. Pogodin
University of Iowa, Iowa City, IA 52242, U.S.A.

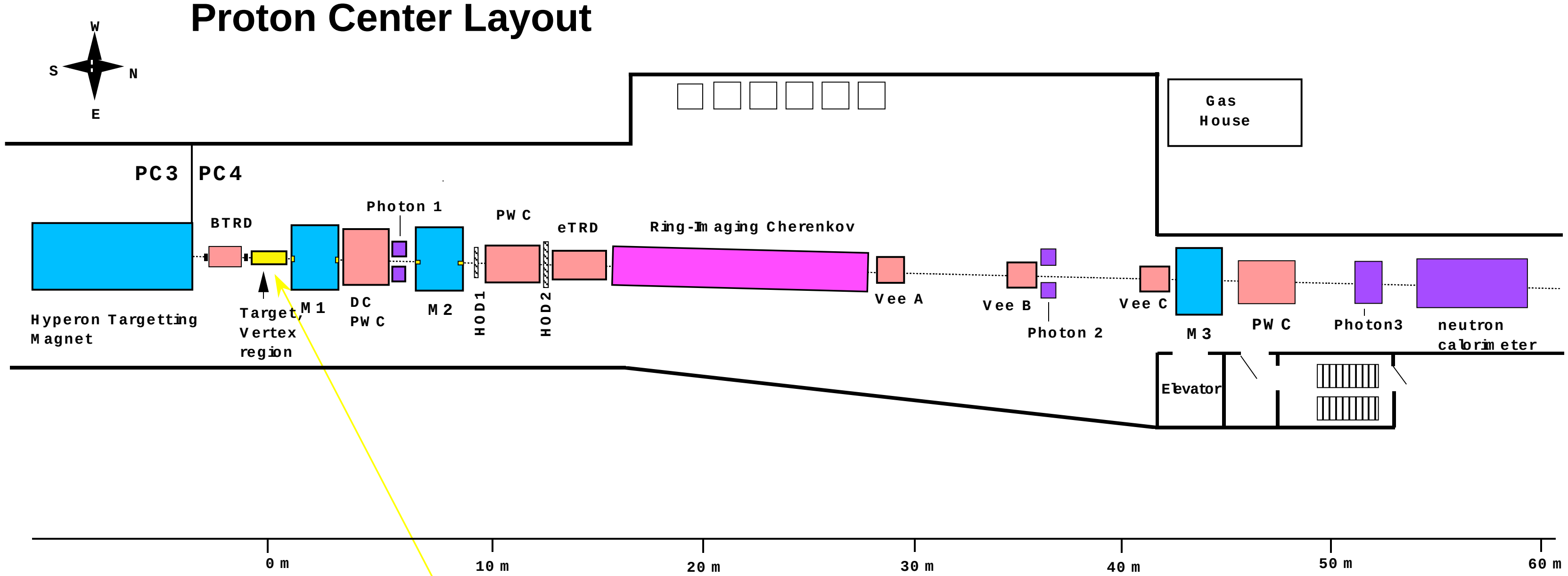
L.J. Dauwe
University of Michigan-Flint, Flint, MI 48502, U.S.A.

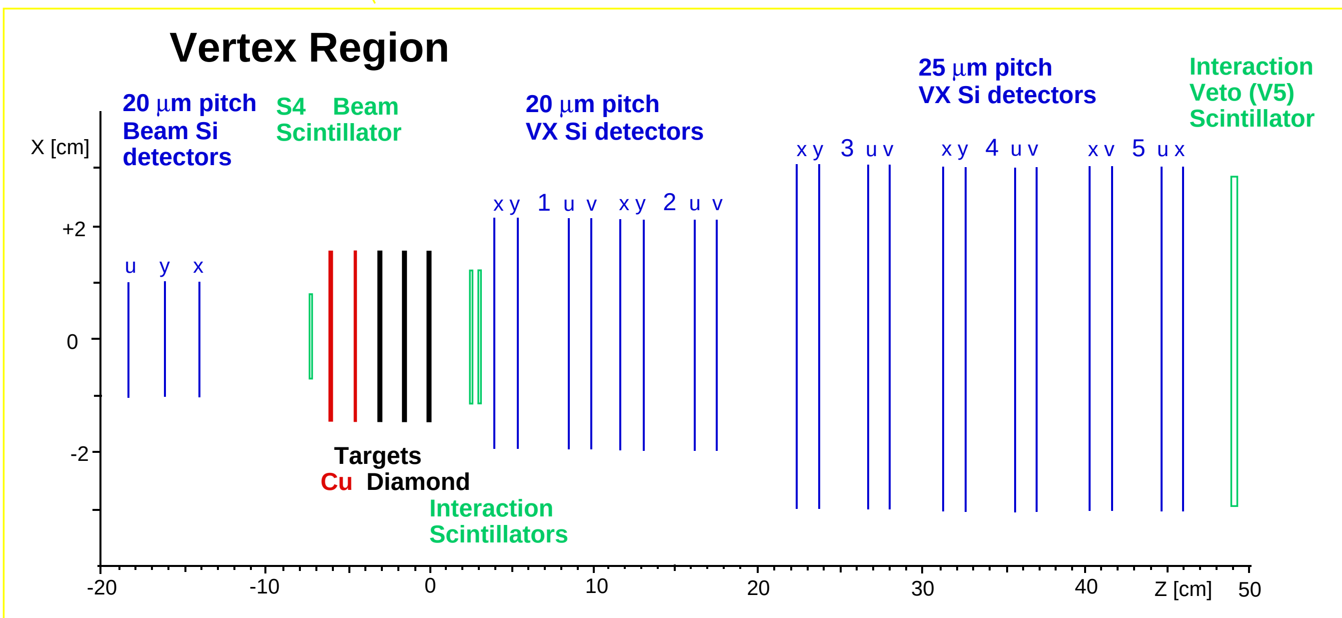
M. Gaspero, M. Iori
University of Rome "La Sapienza" and INFN, Rome, Italy

L. Emediato, C.O. Escobar[14], F.G. Garcia[4], P. Gouffon, T. Lungov[15], M. Srivastava, R. Zukanovich-Funchal
University of São Paulo, São Paulo, Brazil

A. Lamberto, A. Penzo, G.F. Rappazzo, P. Schiavon
University of Trieste and INFN, Trieste, Italy

Selex (E781)
Proton Center Layout





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Nuclear Instruments and Methods in Physics Research A 431 (1999) 53–69

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

The SELEX phototube RICH detector

J. Engelfried[a,*,1], I. Filimonov[b,2,3], J. Kilmer[a,1], A. Kozhevnikov[c,3], V. Kubarovsky[c,3], V. Molchanov[c,3], A. Nemitkin[b,3], E. Ramberg[a,1], V. Rud[b,3], L. Stutte[a,1]

[a] *Fermi National Accelerator Laboratory, Batavia, IL, USA*
[b] *Moscow State University, Moscow, Russia*
[c] *Institute for High Energy Physics, Serpukhov, Russia*

Received 6 November 1998

Abstract

In this article, construction, operation, and performance of the RICH detector of Fermilab experiment 781 (SELEX) are described. The detector utilizes a matrix of 2848 phototubes for the photocathode to detect Cherenkov photons generated in a 10 m neon radiator. For the central region an N_0 of 104 cm^{-1}, corresponding to 13.6 hits on a $\beta = 1$ ring, was obtained. The ring radius resolution measured is 1.6%.

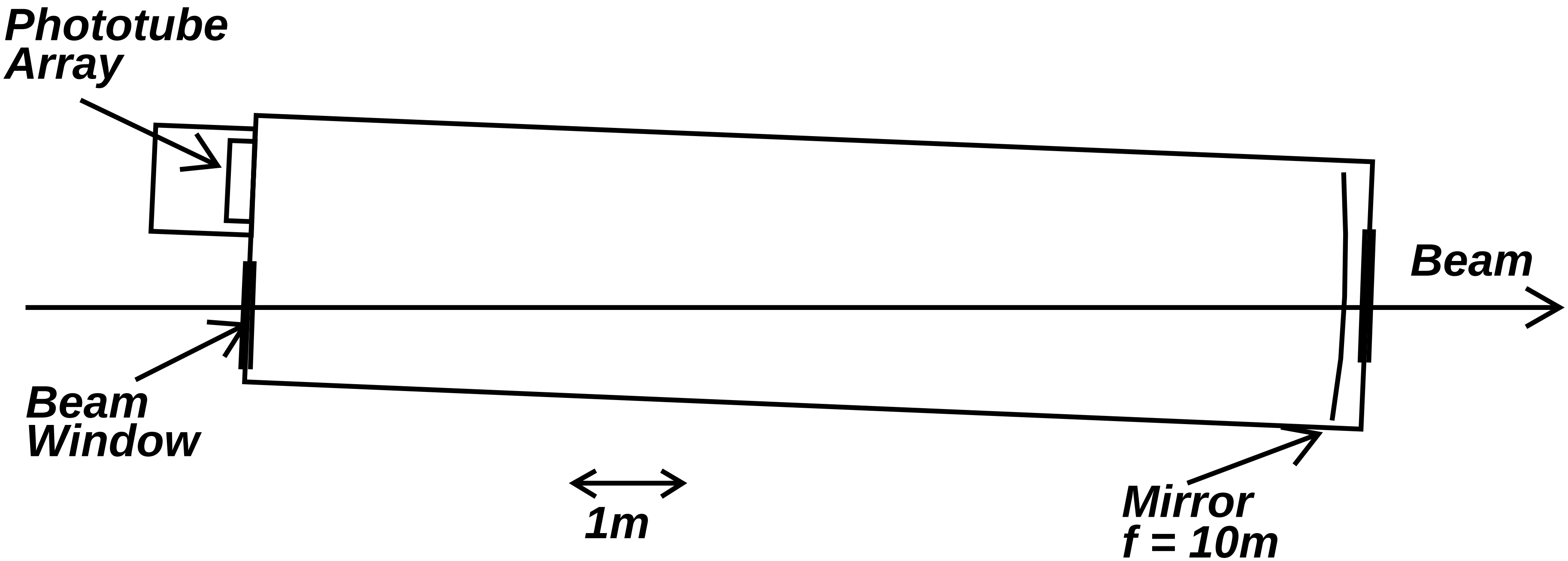
1. Introduction

The Fermilab experiment E781 (SELEX): a segmented large x_F Baryon spectrometer [1,2], which took data in the 1996/1997 fixed target run at Fermilab, is designed to perform high statistics studies of production mechanisms and decay physics of charmed baryons such as Σ_c, Ξ_c, Ω_c and Λ_c. The physics goals of the experiment require good charged particle identification to look for the different baryon decay modes. One must be able to separate π, K and p over a wide momentum range when looking for charmed baryon decays like $\Lambda_c^+ \rightarrow pK^-\pi^+$.

A RICH [3] detector with a 2848 phototube photocathode array has been constructed [4,5] to do this. The detector begins about 16 m downstream of the charm production target, with two

* Corresponding author. Now at Instituto de Física, Universidad Autonoma de San Luis Potosí, Manuel Nava # 6, Zona

SELEX RICH Vessel and Gas System



Vessel: 10.3 m long

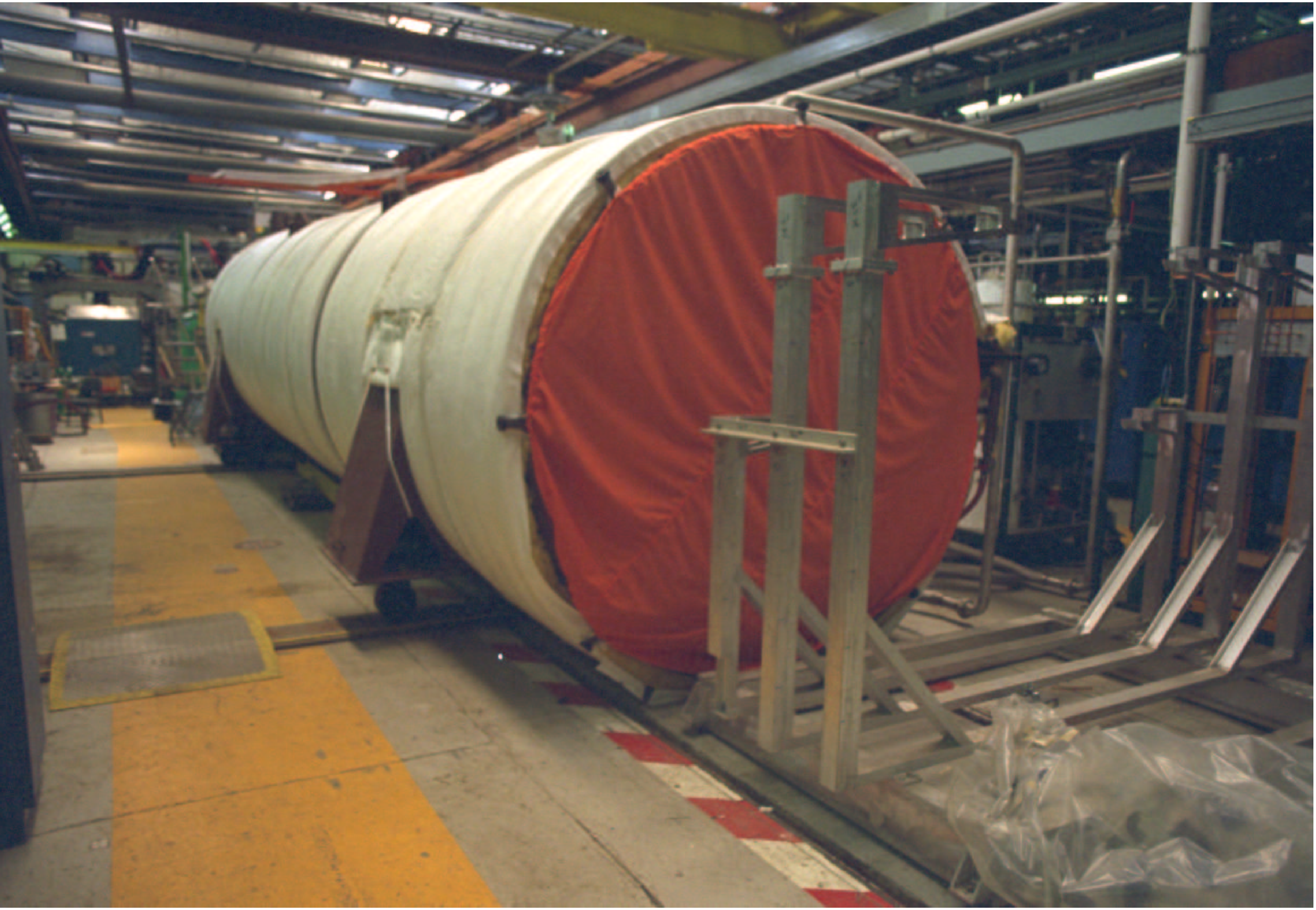
2.4 m diameter (50 m^3)

Gas: Neon @ 1 atm

closed volume ($\Rightarrow$ constant refractive index)

Filling:

- purge with CO_2 ($\approx$ 1 day)
- freeze out CO_2, replace with Ne
- remove remaining O_2 and water
- started with 3 ppm O_2
- after 15 months: (20 ± 12) ppm



SELEX RICH Mirrors

Spherical, nominal 20 m Radius
16 hexagonal mirrors, 46 cm tip to tip

- Glass
  - low expansion glass (Schott Tempax), 10 mm thick.
  - Polished to 19.82 m $\pm$ 5 cm
  - Measured with Ronchi Method (NIMA 369 (1996) 69-78)
- Coating
  - Aluminum, with MgF_2 overcoating (Acton)
  - Reflectivity $> 85\,\%$ at 160 nm
- Mounting
  - 3 point mount
  - Ball bearing, double differential screw
  - Honeycomb panel with carbon fiber matrix
- Alignment
  - Theodolite with Laser in Center of Curvature
  - Vessel movable on wheels lateral to beam

Reprinted from

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A

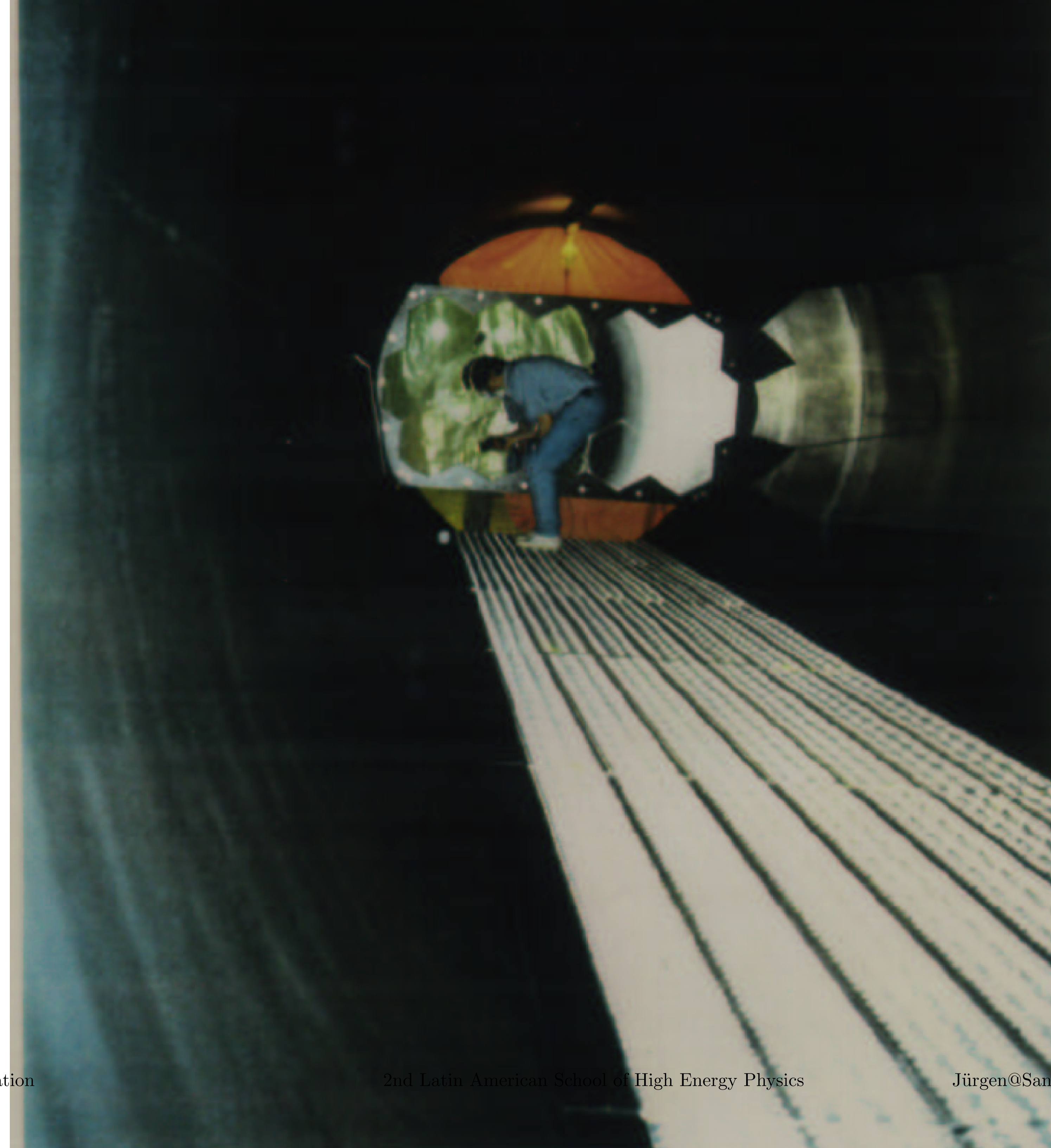
Nuclear Instruments and Methods in Physics Research A 369 (1996) 69–78

A method to evaluate mirrors for Cherenkov counters

Linda Stutte*, Jürgen Engelfried, James Kilmer

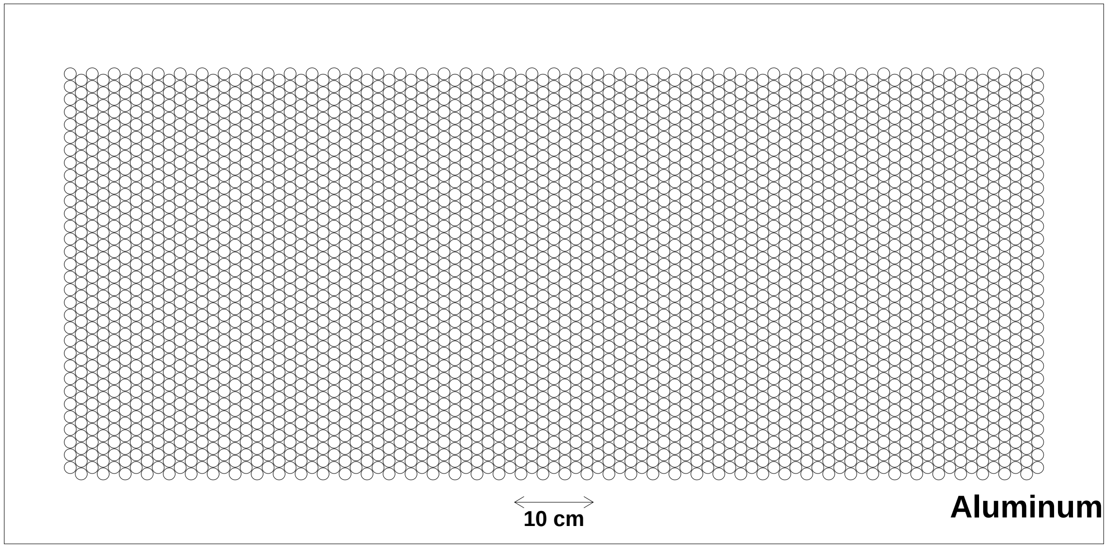
Fermi National Accelerator Laboratory[1], *P.O. Box 500, Batavia, IL 60510, USA*

Received 19 June 1995

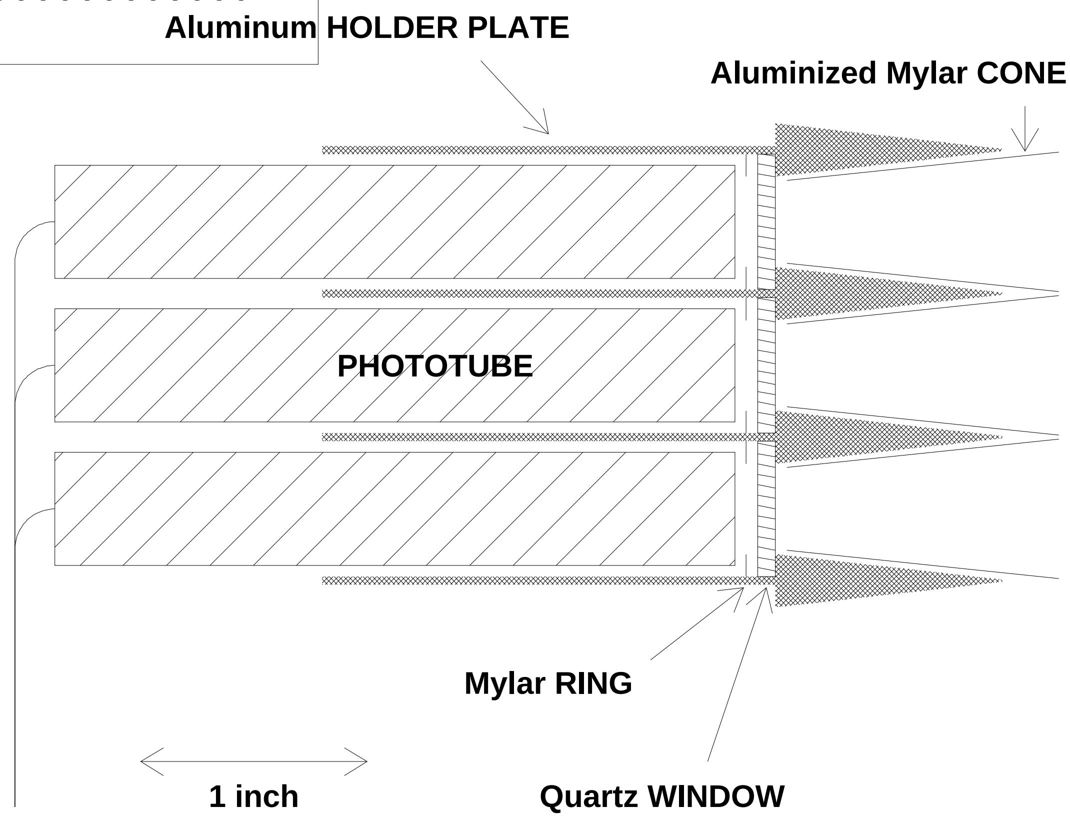


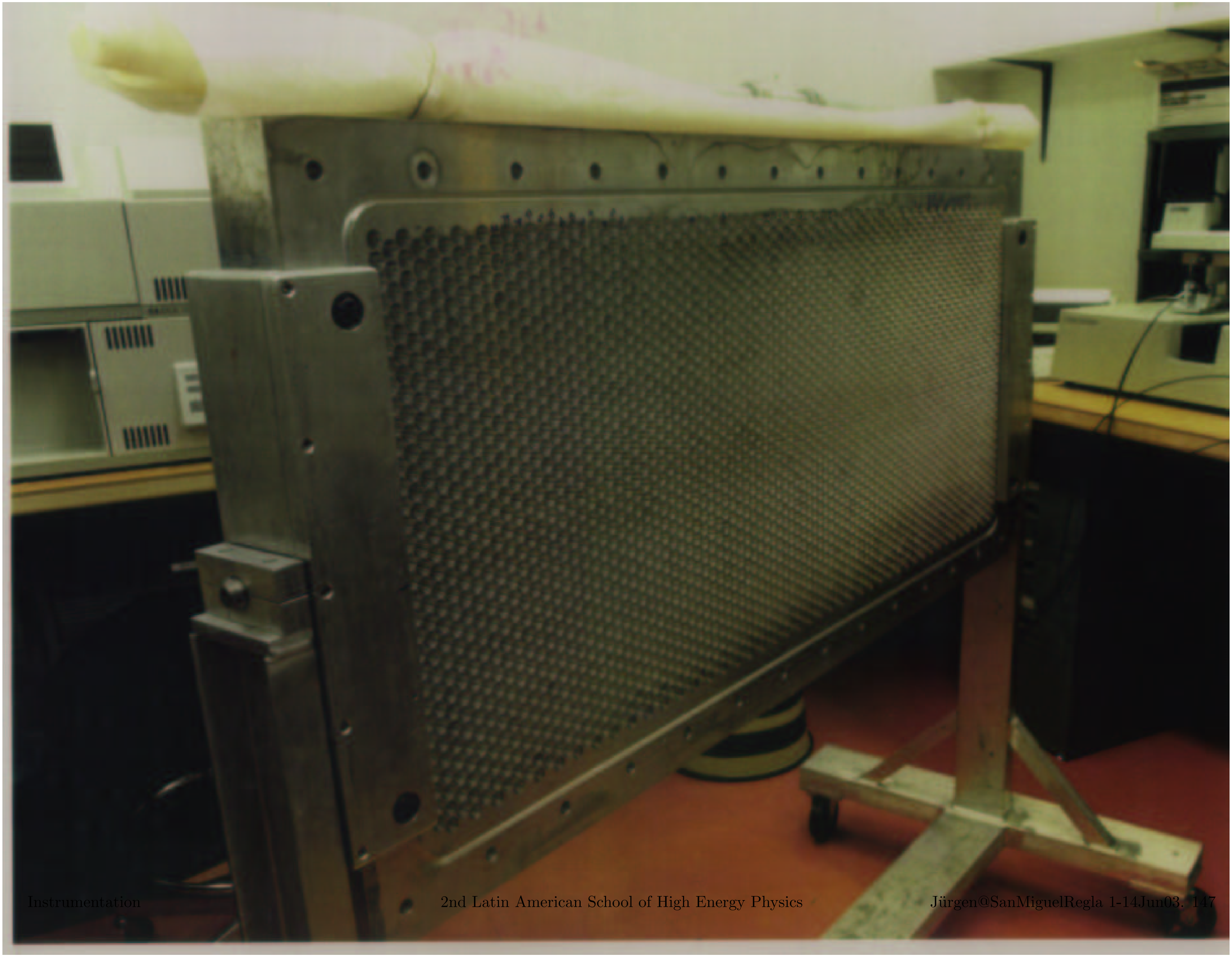
SELEX RICH Photon Detection

- Photomultiplier Holder
  - Aluminum plate, 2848 (89×32) holes
  - individual quartz windows as gas seal
  - aluminized mylar Winston cones
- Photomultipliers
  - $\frac{1}{2}$" diameter, Photocathode 10 mm
  - 608 Hamamatsu R760
  - 2240 FEU60 (with wavelength shifter)
  - all PM measured to find operating voltage
  - groups of 32 run on same HV
- High Voltage
  - Operating Voltage 900 V...1900 V
  - 6 HV Supplies
  - Zener Box (á la "Berkeley Cow"), 96 outputs
- Crates with Hybrid Chips
  - Hybrids contain Amplifier, Discriminator, diff. ECL Driver
- Readout: CROS PWC System
  - Integration time 170 nsec

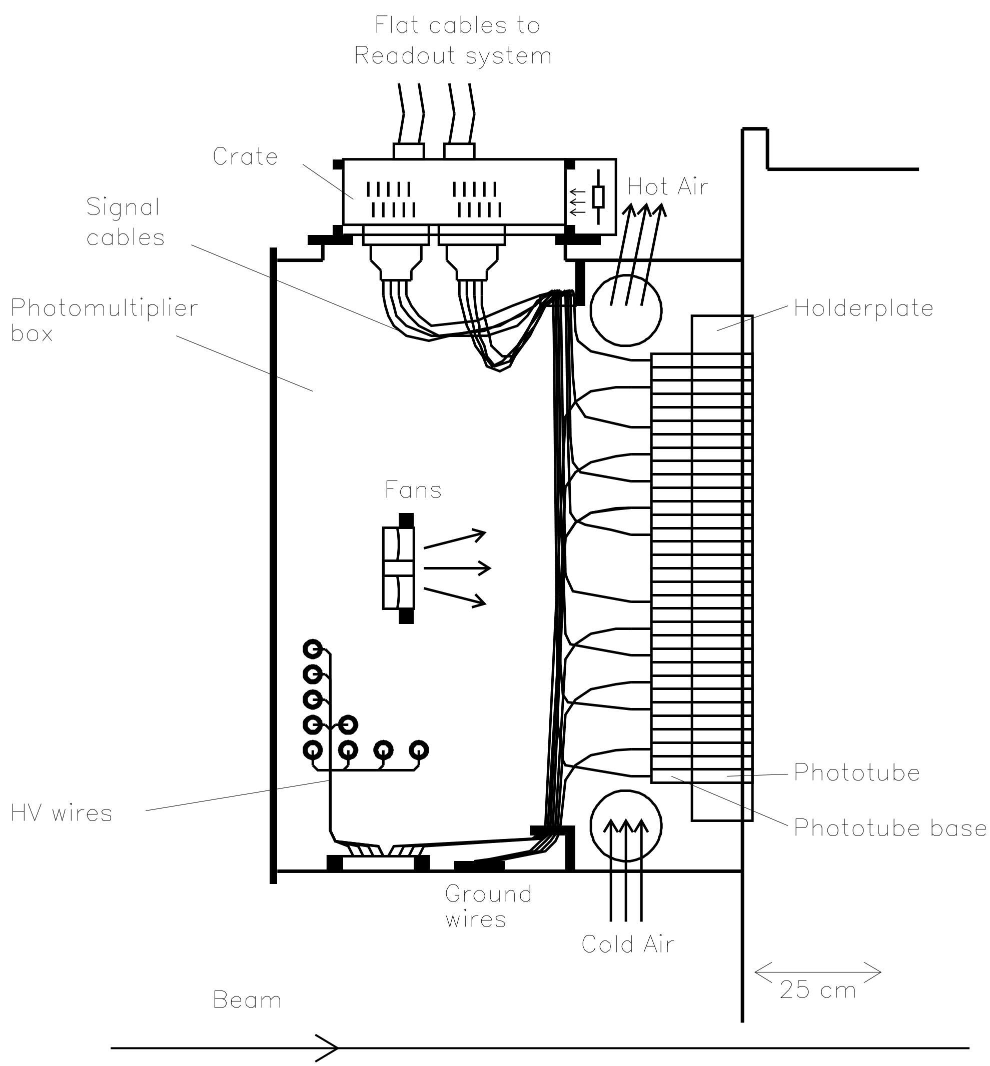

10 cm

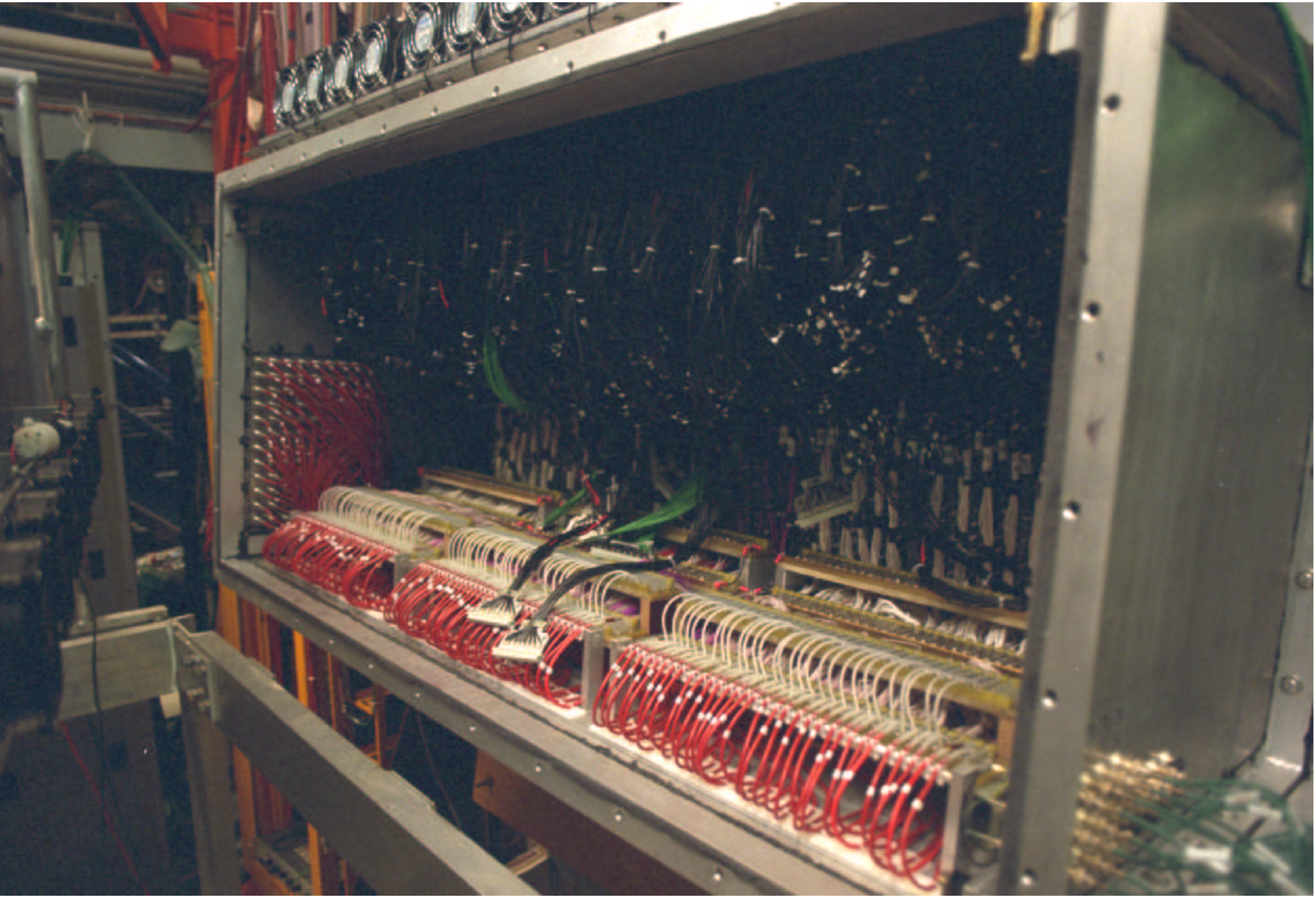

HAMAMATSU
Photomultiplier
Tube
TYPE R760
No. EA111

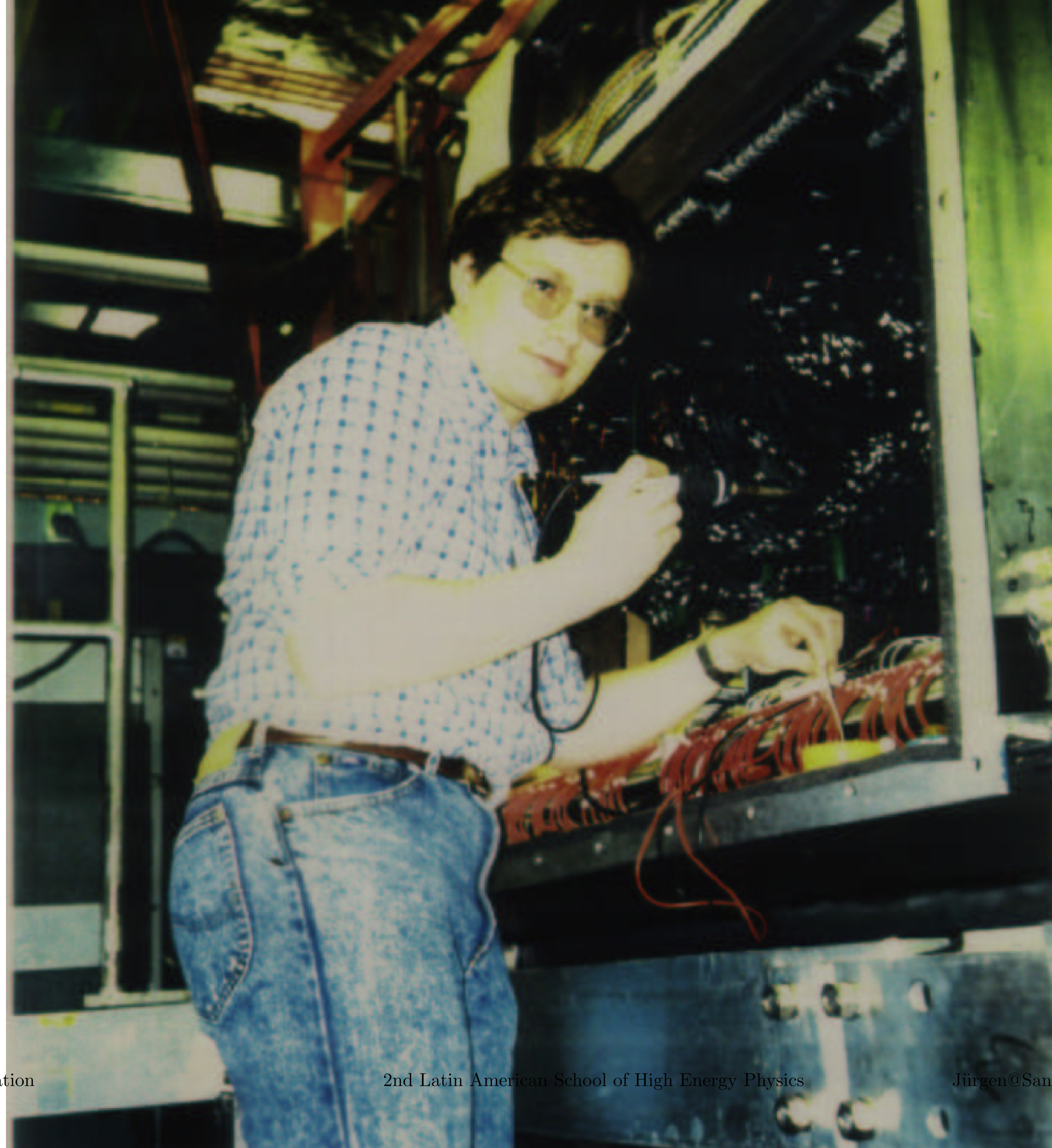

Aluminum HOLDER PLATE
Aluminized Mylar CONE
PHOTOTUBE
Mylar RING
1 inch
Quartz WINDOW



SELEX RICH PM Box



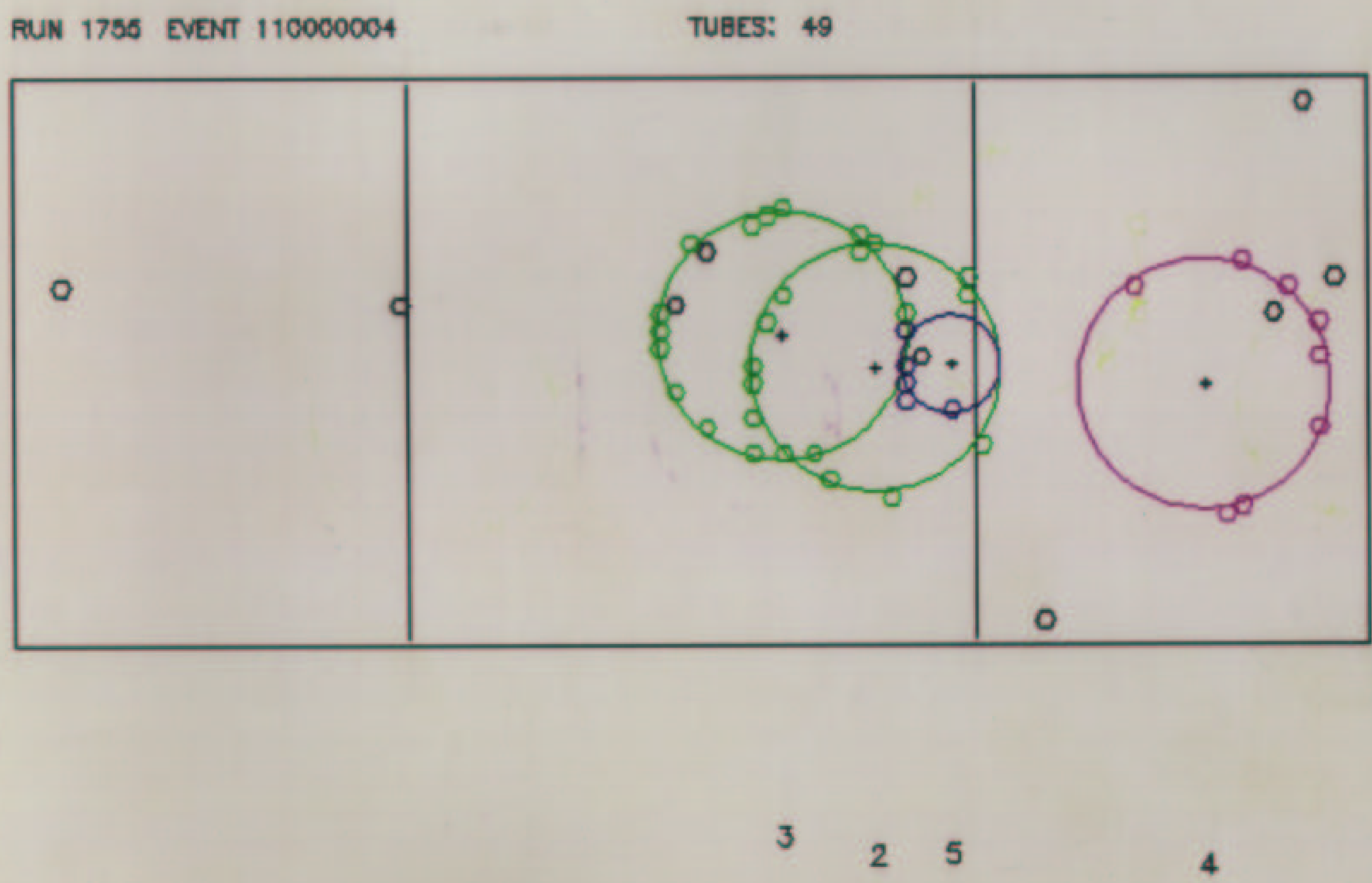




trk	momnt	pid	pckge	stat	gam	bckg	e	muon	pion	kaon	p	sigma
1	71.4	5	rich	8	-1.00	0.00	0.79	1.00	0.88	0.00	0.00	0.00
2	-136.8	9	rich	8	-1.00	0.00	0.88	0.96	1.00	0.00	0.00	0.00
3	-38.1	9	rich	8	-1.00	0.00	0.00	0.06	1.00	0.00	0.00	0.00
4	50.0	8	rich	8	-1.00	0.00	0.24	0.81	1.00	0.00	0.00	0.00
5	-107.7	12	rich	8	-1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

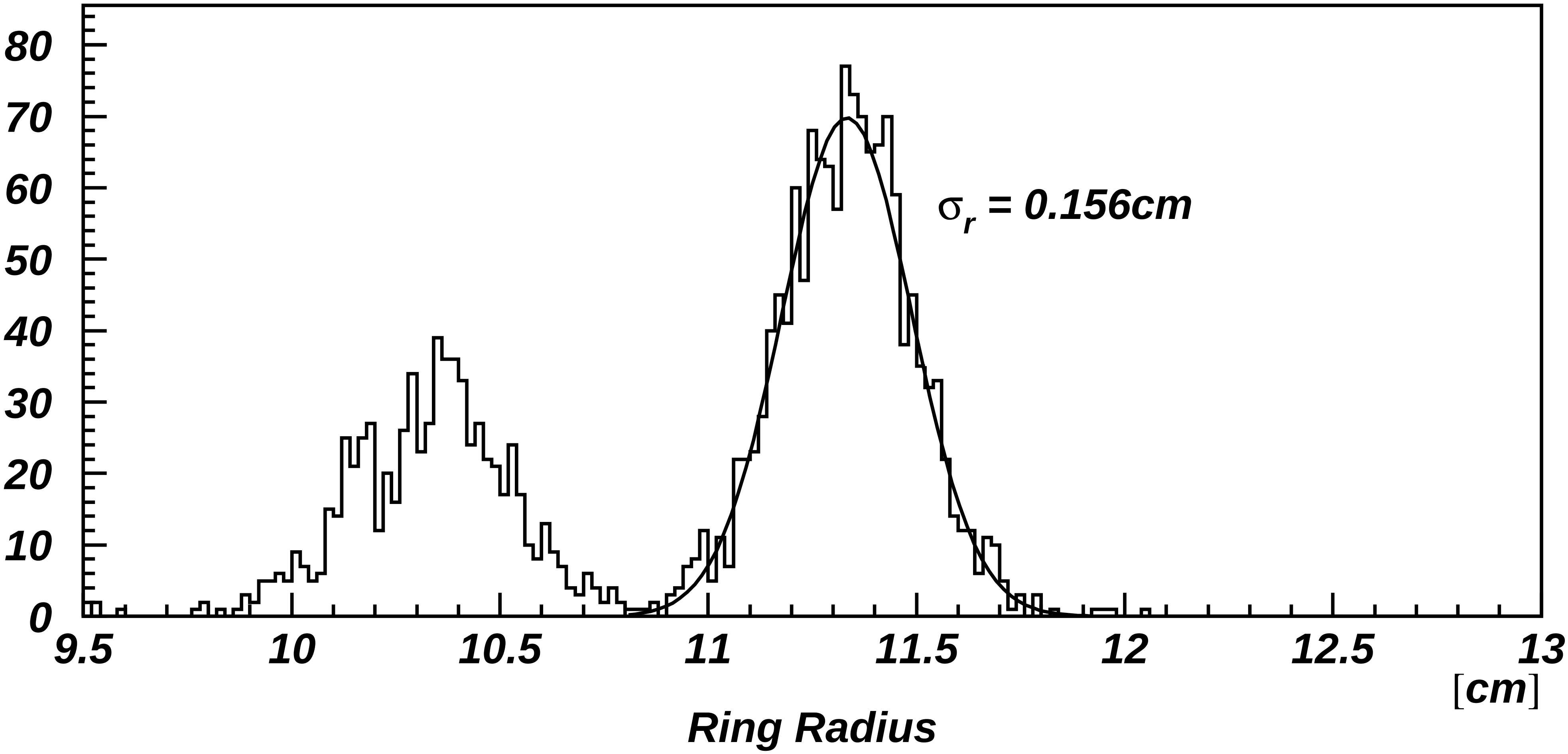
RUN 1755 EVENT 10000030 TUBES: 67

trk	momnt	pid	pckge	stat	gam	bckg	e	muon	pion	kaon	p	sigma
2	-81.9	9	rich	8	-1.00	0.00	0.75	0.96	1.00	0.00	0.00	0.00
3	-120.2	9	rich	8	-1.00	0.00	0.61	0.82	1.00	0.00	0.00	0.00
4	-22.5	3	rich	8	-1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
5	-88.1	15	rich	8	-1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

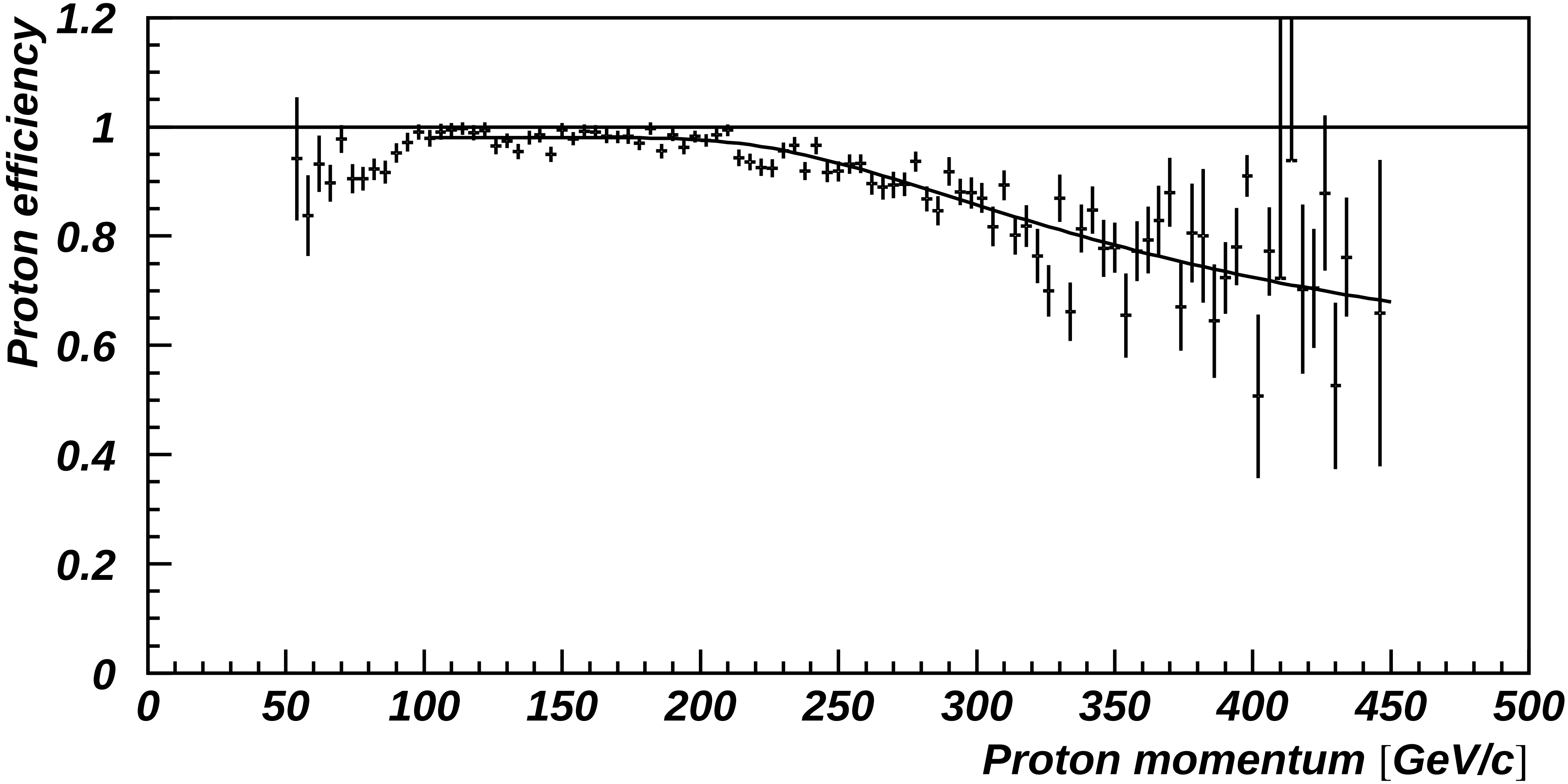


SELEX RICH Separation

Momentum of particles: $95\,\mathrm{GeV}/c - 105\,\mathrm{GeV}/c$



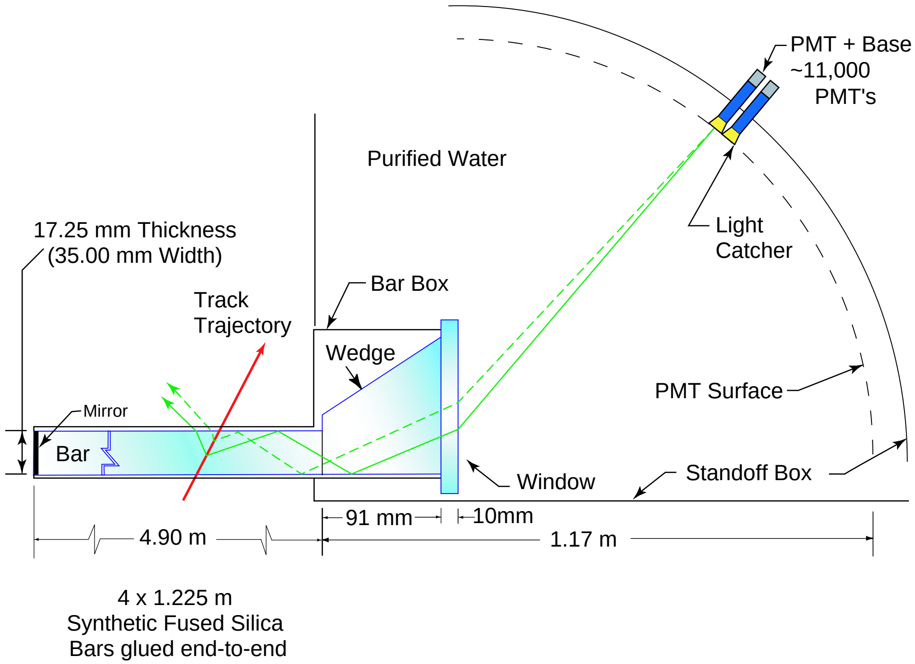
SELEX RICH Efficiency – Protons

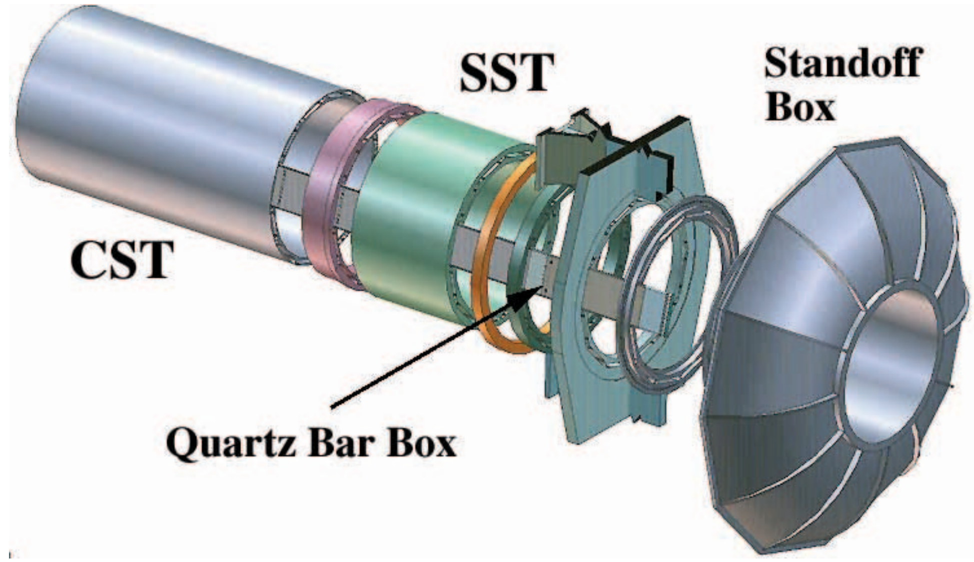


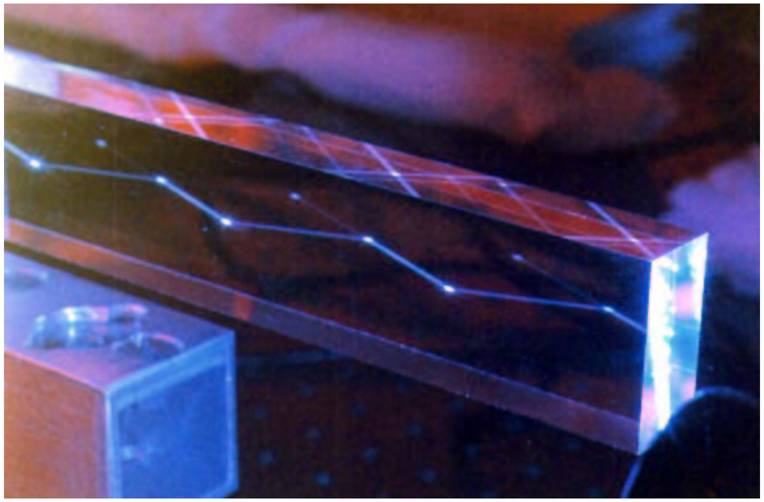
A Current RICH: DIRC at BaBar

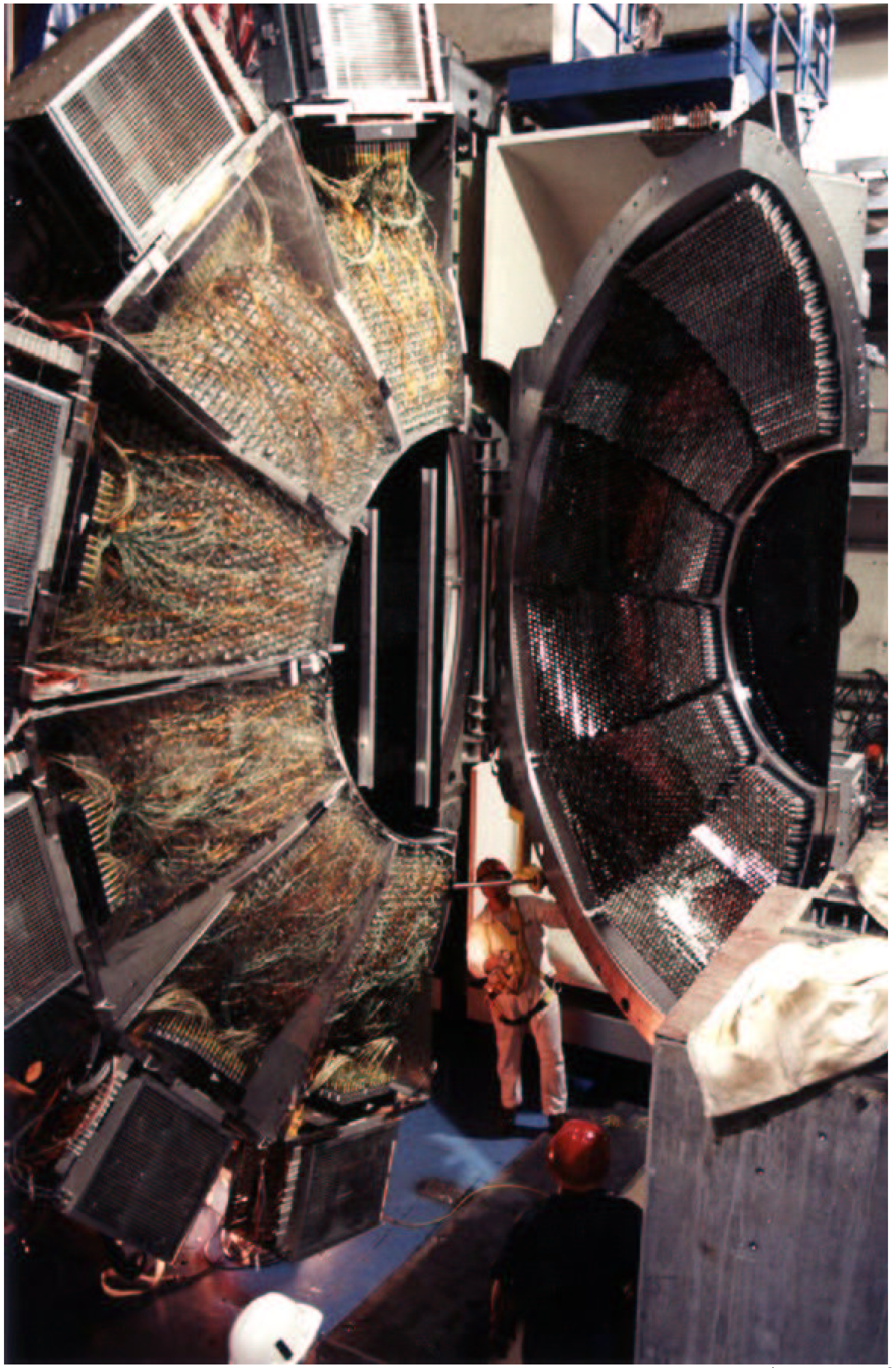
DIRC at BaBar

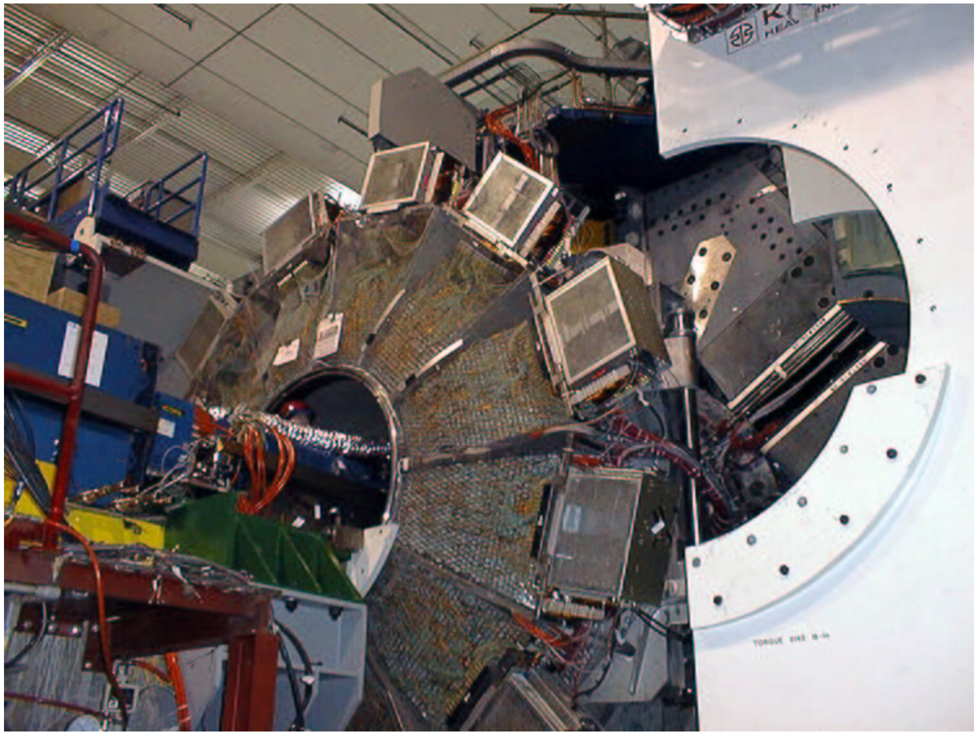
Detection of internally reflected Cherenkov light



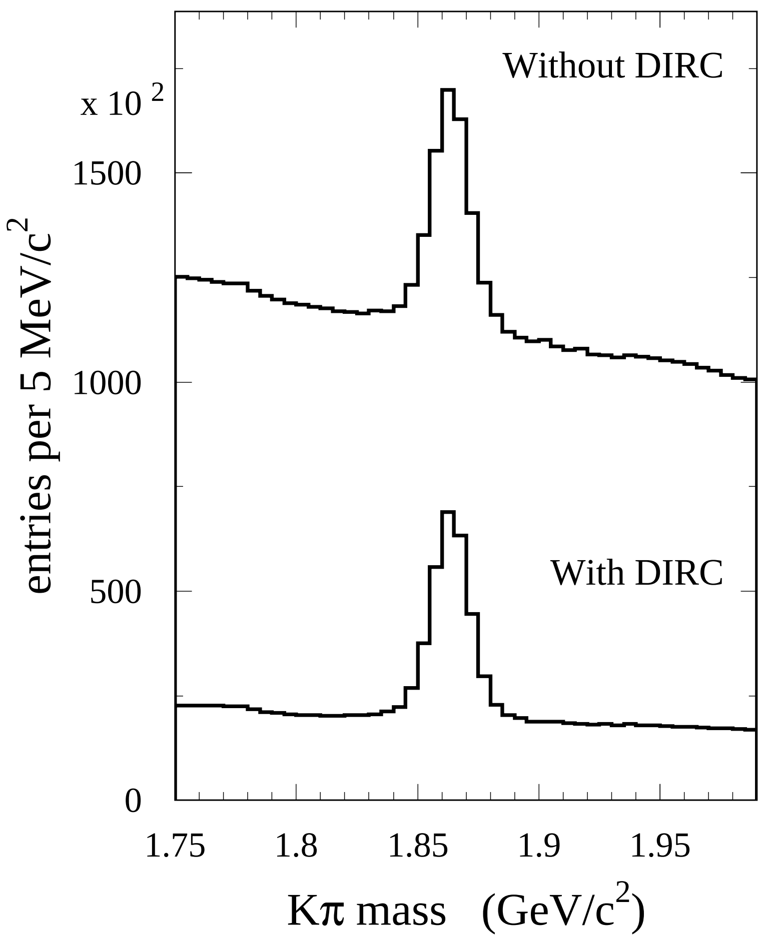


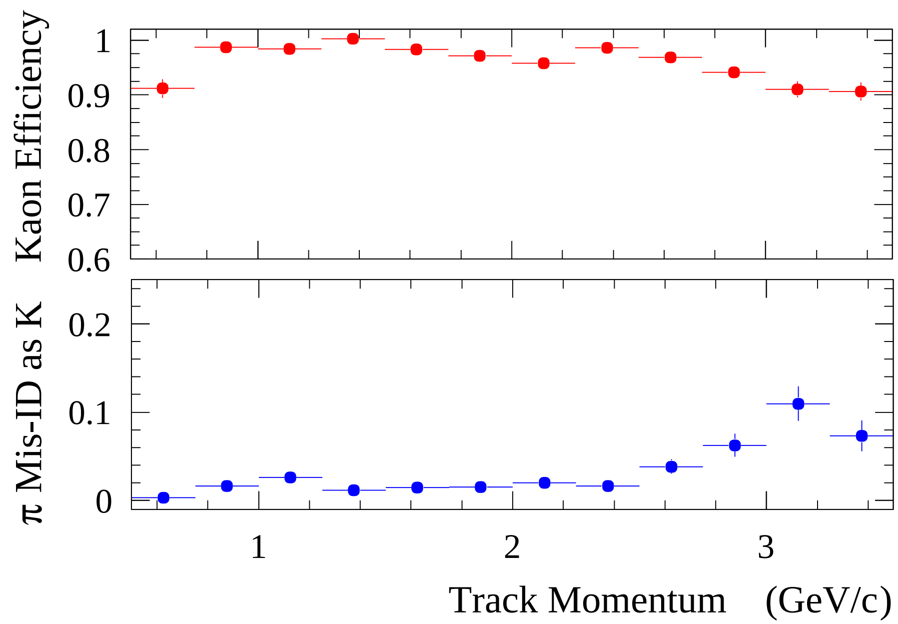






DIRC at BaBar – Performance

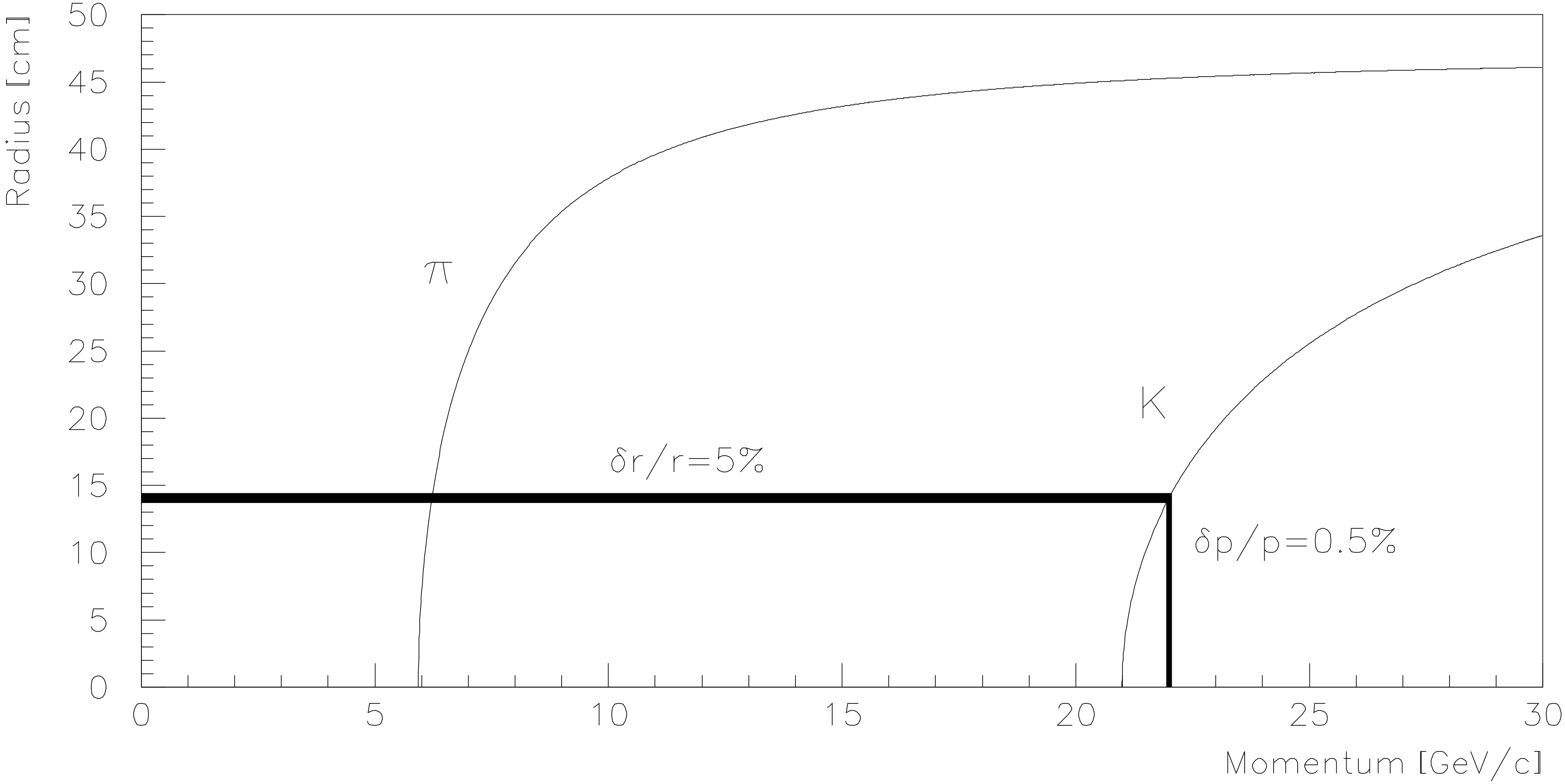




Future in RICH and México: CKM RICHes

Future Use: CKM

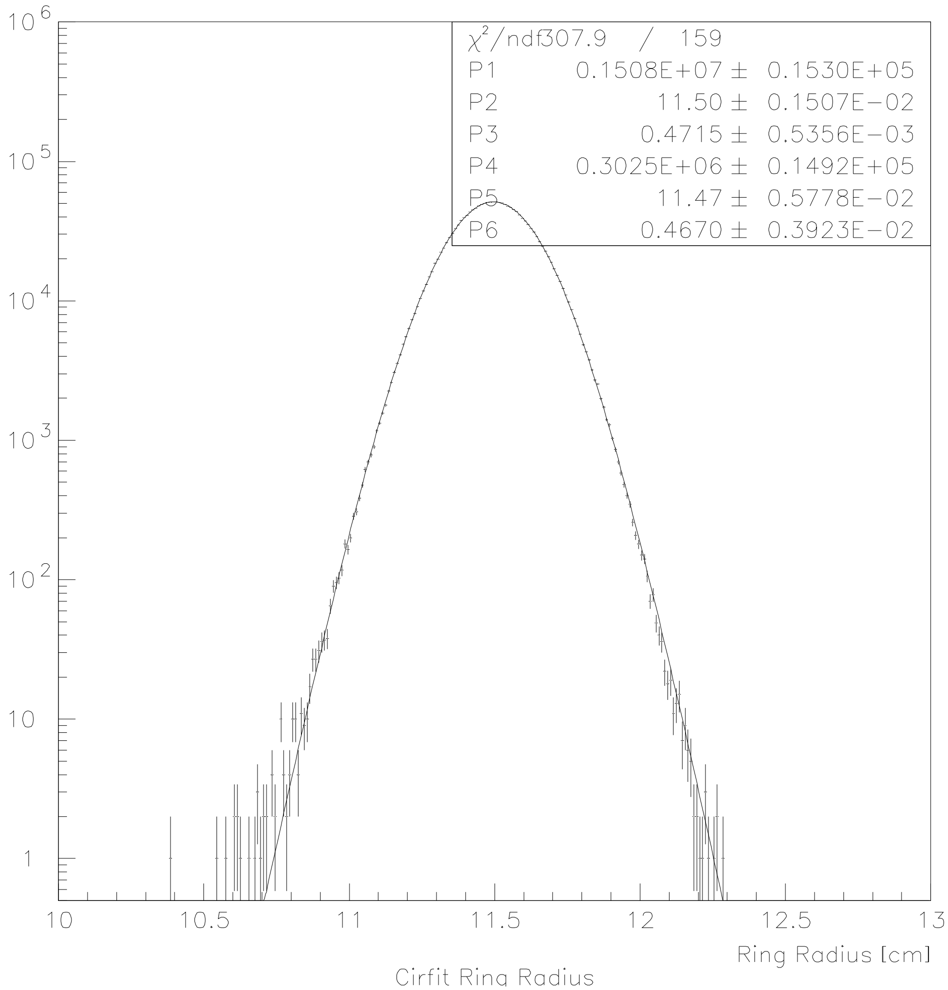
Will use 2 RICHes to really measure velocity. Particle ID comes for free.



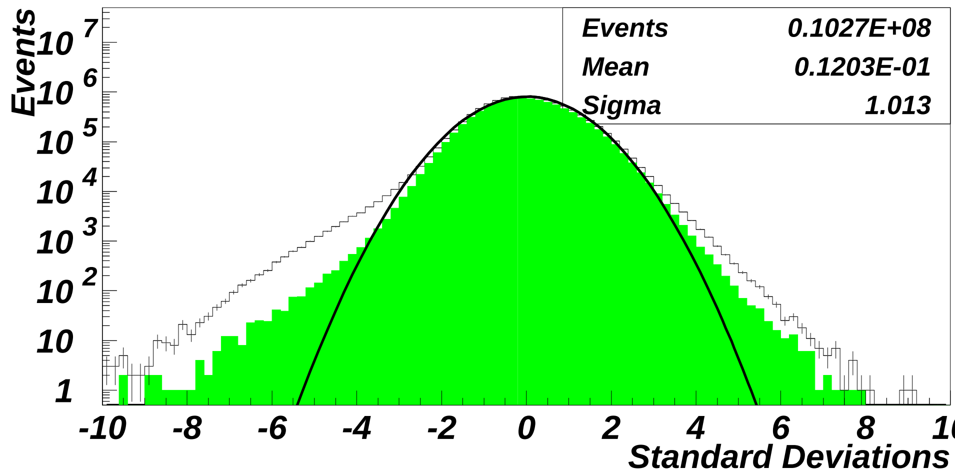
How Gaussian is the response?

A Study with SELEX single beam tracks

SELEX Standard Algorithm



Standalone Pattern recognition



Gaussian over nearly 5 orders of magnitude!

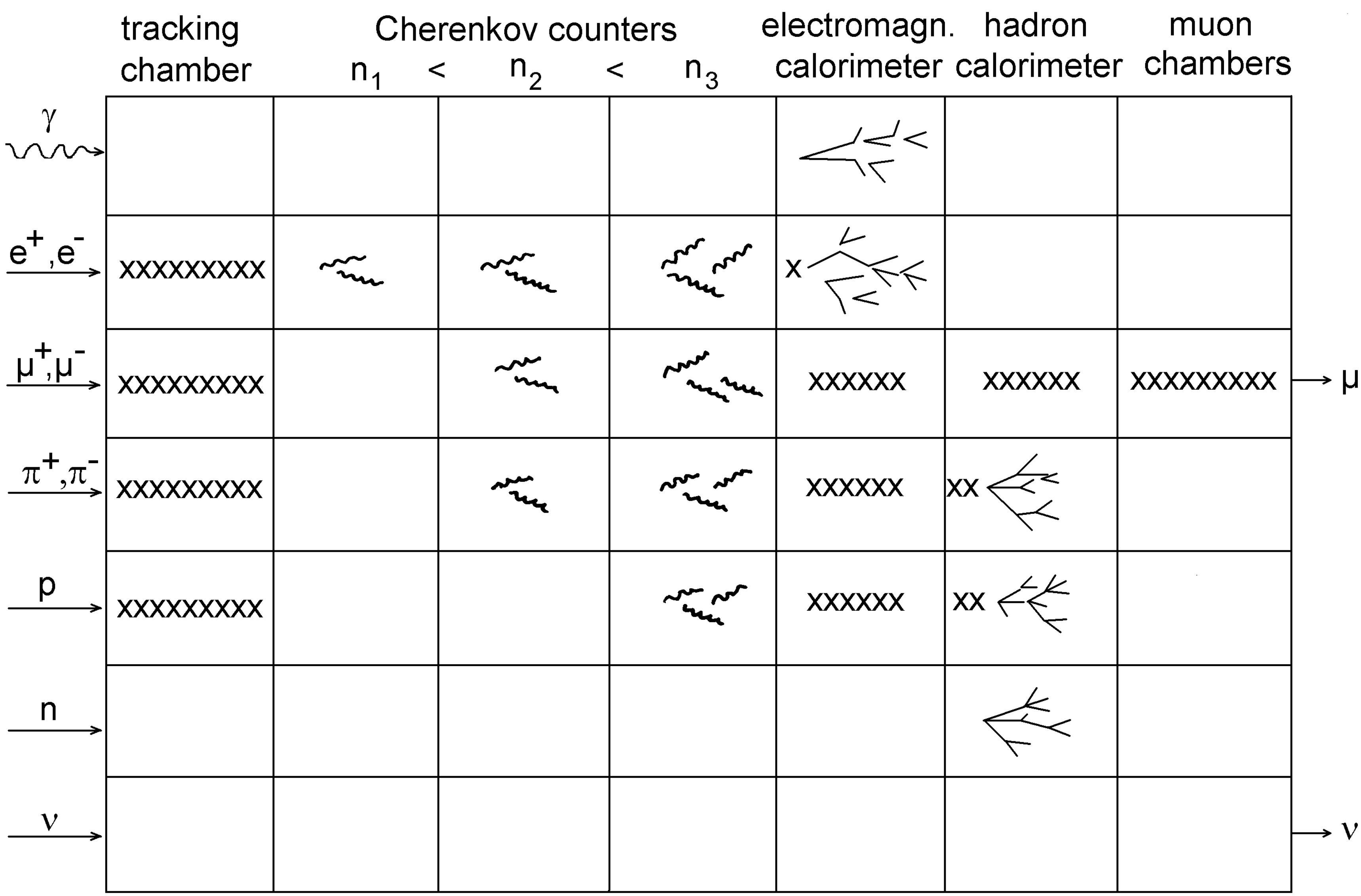
Involvement of San Luis Potosi Group in CKM

- Design work on Kaon and Pion RICH
- Mechanical parts for CKM RICH Prototype
- Monte Carlo studies (experiments, RICH detectors)
- Construction of flat, thin mirror for Kaon RICH
- Tests and Classifications of Photomultipliers
- (Maybe:) Supervision of spherical mirror production for Kaon and Pion RICH (in Mexico?)

Summary Particle Identification

- Particle Identification (for charged particles) usually measures the velocity of the particle, identification is combined with the already known momentum.
- Transition Radiation Detectors mostly used in beamlines, but also to measure decay products (mostly electron–pion separation)
- Cherenkov effect is used in Threshold Cherenkov Counters
- Cherenkov effect is used in RICH detectors
- RICHes are an established standard detector now, and have a bright future.

Summary Particle Identification (cont.)



That's it.....

Conclusion and Reminder what we have seen

- First Part: Physics of Particle Detection
  - Interaction of Charged Particles
    - Ionization, scintillation, Cherenkov and Transition Radiation
    - Bremsstrahlung and nuclear interactions
  - Interaction of Neutral Particles
    - photons: photoelectric effect, Compton scattering, pair production
    - neutrons
    - neutrinos
  - Electromagnetic Showers
  - Hadron Showers

- Second Part: Basic detector designs
  - Gaseous detectors (wire chambers)
  - Silicon Microstrips
  - Calorimeters
  - Electronics
  - Simulation

- Third Part: Particle Identification
  - Involves lot of instrumentation
  - RICHes are established
  - Instrumentation can be done in Latin America